CERTAIN PHYSICAL AND STRUCTURAL PROPERTIES OF THREE SPECIES OF SOUTHERN YELLOW PINE CORRELATED WITH THE COMPRESSION STRENGTH OF THEIR WOOD[1]

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There is a growing demand among lumber consumers for maximum strength values per unit volume of material and more reliable working stresses for structural timbers. This situation, allied with the rapid depletion of virgin growth timber, has made it difficult for the lumberman to meet the requirements of commerce without a more perfect knowledge of the factors influencing the strength and usability of wood than he has had in the past. Numerous researches, beginning with that of Parent about the year 1707, have been made on the mechanical properties of wood. Fernow ('92) summarized the earlier works, and the more recent investigations have been covered by The National Committee on Wood Utilization ('29) and by Withey and Aston ('30).

Defects in the form of knots and shakes have a definite effect upon the strength of beams, depending upon the size, condition, and position of the imperfections (Newlin and Johnson, '24). Spiral- and cross-grain have a decided effect upon strength and elastic properties, depending upon the angle at which the fibers lie in relation to the axis of the test stick (Wilson, '21).

The strength properties of clear wood have a certain relation to the specific gravity (density) regardless of species (Newlin and Wilson, '19, and Markwardt, '27), but it is readily observed

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that this relationship has definite limitations. For wood in general there may be a variation in compression strength of from 2000 to 3000 pounds per square inch for a given density. Wood taken from trees of the same species, and even from the same tree, has a variation of from 40 to 70 per cent (based upon the minimum strength) for a given specific gravity.

The purpose of this investigation on the wood of southern yellow pine was to determine the causes of these variations and if possible to describe them so that their presence might be recognized without first testing the material. It was found that the variations may be attributed to two sets of variables which, though interlocking, may be roughly outlined, as (1) the physical condition and chemical constituents of the cell wall, and (2) the anatomical structure of the wood. The physical conditions include the fiber-saturation point, the moisture content, the absolute density of the wood substance, and the percentage of resin affecting the specific gravity. Anatomical differences in the southern pines were the relative amounts of thick- and thin-walled fibers in a given area as determined by rate and type of growth, the size and distribution of resin ducts and wood rays, the length and diameter of the tracheids, and the structure of the cell walls. In evaluating the strength on the basis of structure, all specimens containing visible defects in the form of knots, checks, and shakes, and cross-grain of more than 1 in 25 were not used. A knowledge of the fiber-saturation point was necessary in order to eliminate moisture effects on strength. In addition, the specific gravity was corrected for benzol-soluble compounds in order to get the true relationship between the density and strength, since this was the most accurate measure of the relative mass of the different specimens. No attempt was made to study the chemistry of the cell wall.

MATERIALS

The seven trees used in this study were selected by representatives of the American Creosoting Co., and the writer is indebted to these men for the data to be found in table I. Three species of southern yellow pine were included: *Pinus Taeda* L. (loblolly pine, trees 1, 2, 5, and 7), *Pinus echinata* Miller (shortleaf pine, tree 3), and *Pinus palustris* Miller (longleaf pine, trees 4 and 6).

One 32-ft. log was taken from the butt portions of trees 1, 2, 3, and 4, whereas three 8-ft. logs were taken in trees 5, 6, and 7, one at the butt, one from the top of the merchantable timber, and the third midway between the other two. In the latter group (trees 5, 6, and 7), note was made of the distance of each 8-ft. log from the stump. The seven logs collectively covered a range of 68 feet from the stump, so that the material was sufficient to make a comparative study of the distribution of strength throughout the merchantable timber.

Each of the logs was marked as to compass direction and tree number when cut, and samples of leaves and cones were collected from each tree for botanical identification. The ends were painted to prevent drying out, and care was taken to preserve the bark intact. They were shipped in the log to Philip Gruner Bros. Lumber Co., St. Louis, where they were sawed into test sticks for the laboratory. For purposes of identification, each log was considered as divided into 4-ft. lengths called bolts which were consecutively lettered *a, b, c,* etc., beginning at the butt. Bolt *a* in each tree represented the first 4 feet from the stump, *b* the second 4 feet (the segment between 4 and 8 feet), *c* the third segment between 8 and 12 feet, and bolt *q* represented the segment betwen 64 and 68 feet (fig 1a).

Each bolt was outlined on the larger end (fig. 1b) from north to south through the pith and from east to west, in order that 4 series of specimens across the entire stem in the two directions could be identified. The lines were drawn at intervals of two inches, which allowed room for sawing and dressing the sticks. The individual specimens were then marked by tree number, bolt letter, compass direction, and distance from the pith. From the pith to the bark on the north and south sides there were two series of specimens numbered 1, 3, 5, 7, etc., and 2, 4, 6, 8, etc., respectively (fig. 1b). The same was true for the east and west sides beginning with the second specimen from the pith. Adjacent to each of these was a second series bearing sub-numbers. The latter series was available only in the larger trees. For example specimen 3eE3 from tree 3, bolt *e*,

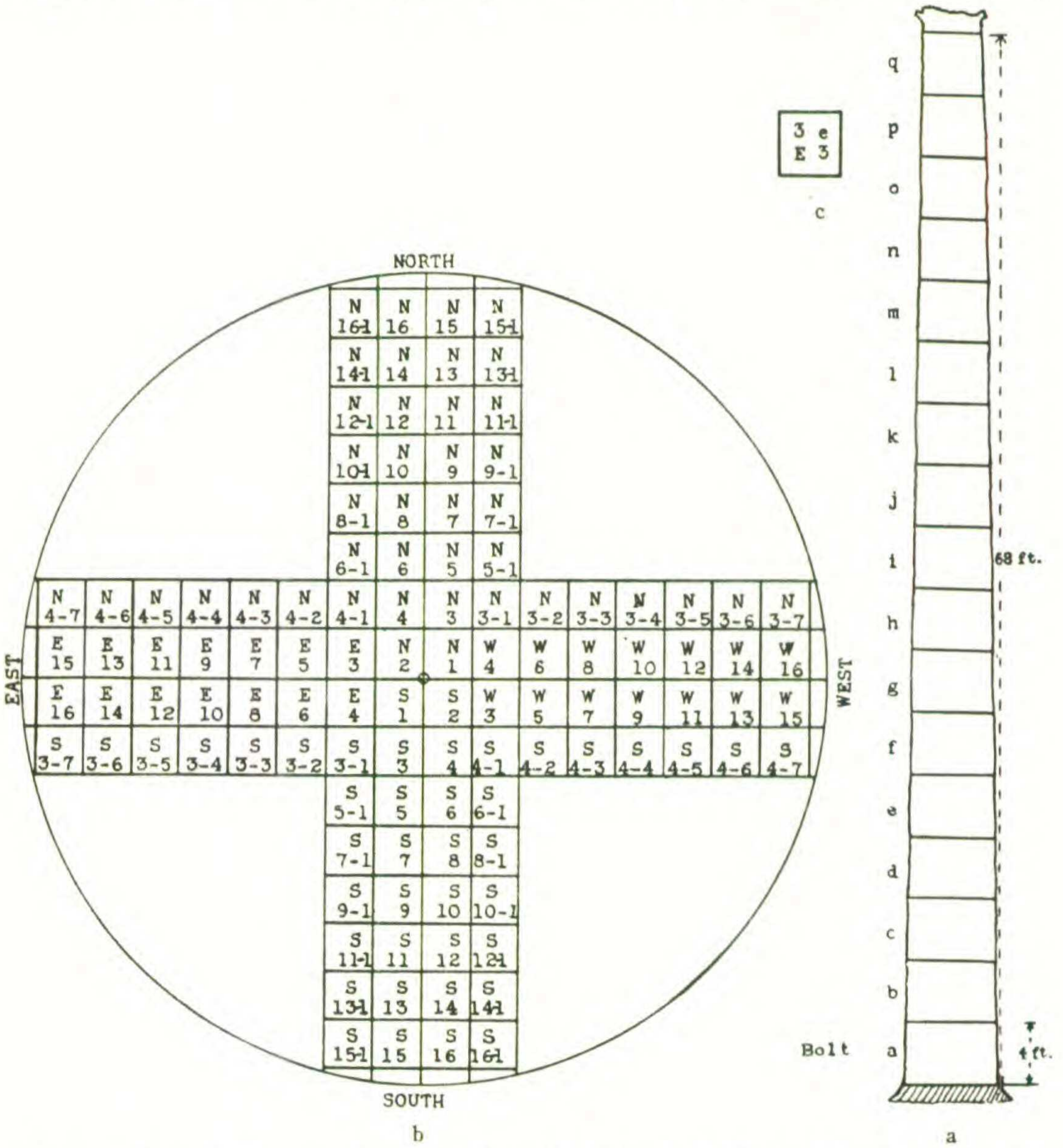

Fig. 1. A diagrammatic sketch showing the method of selecting and marking test specimens. *a*, the trunk of the tree divided into bolts; *b*, the cross-section of a bolt, showing the method of labeling; *c*, a typical specimen with complete markings. The specimen indicated was from tree 3, bolt e, on the east side, and was the second specimen from the pith.

on the east side of the tree, with its center 3 inches from the pith, would be marked as shown in fig. 1c. The first figure in any specimen number or identification mark refers to the tree number, the first letter (which is always a small letter), to the bolt, the second letter (always a capital), to the compass direction, and the last figure or series of figures (as in 5bN3-3) gives the position along the radius or distance from the pith.

The method of marking specimens is in accord with the recommendations of the American Society for Testing Materials, except that the marking was done on the bottom or larger end of the bolt in order to save all specimens six inches or more in length in the outer sapwood.

The material tested green was surfaced at once and stored in wet sawdust in the laboratory during the period of testing. Moisture samples were taken from each test stick immediately on receipt at the laboratory in order to get a measure of the moisture distribution in the green tree. The material tested dry was allowed to season about three months in the rough, then surfaced and stored in the laboratory until tested. The material from trees 1 and 2 was kept in the laboratory for about a year before the tests were made.

Physical Properties

THE FIBER-SATURATION POINT

The fiber-saturation point of wood may be defined as the state in which the wood substance is saturated throughout without moisture existing as free water in the lumina of the cells or intercellular spaces. Theoretically, the physical properties of the wood fiber should not change with further additions of water since it would only displace the gases in the free spaces. Bearing in mind the fact that resins and oils present in the pine wood are not soluble in water, it can readily be seen that a perfect gradient of moisture, which is necessary in order to locate the exact point of saturation, is very difficult to obtain. The more common methods of measuring the fiber-saturation point are based upon either the change in volume of the specimen, the change in strength properties, or upon the change in specific conductance, all of which agree in general but vary over a wide range for any given specimen due to moisture gradients in the sample. The relationships of moisture-volume, moisture-strength, and moisture-conductance all show a sharp change in rate at the fiber-saturation point. The advantage of the electrical measurements is that very small specimens can be used, and thus a more perfect distribution of moisture can be obtained.

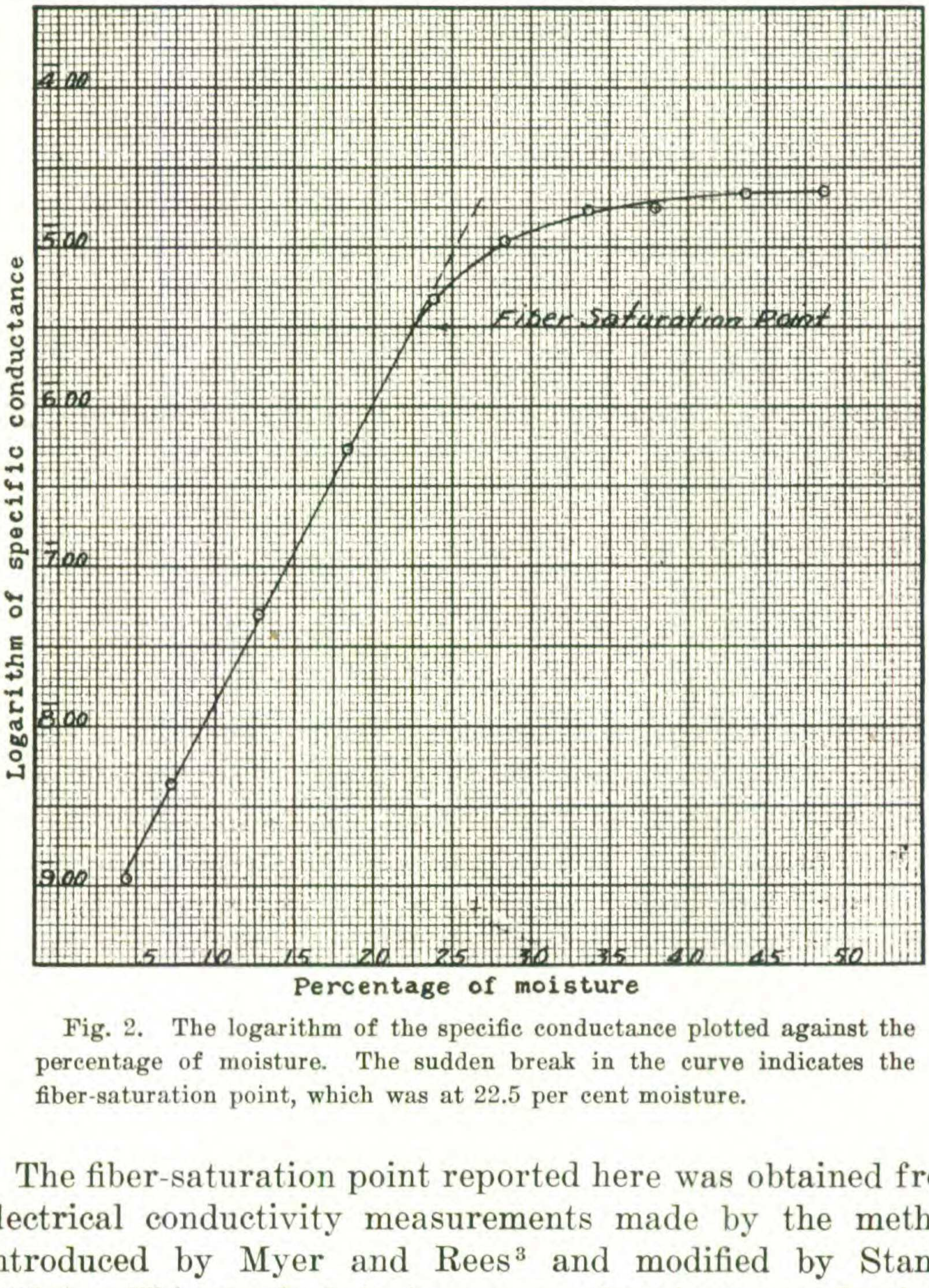

Fig. 2. The logarithm of the specific conductance plotted against the percentage of moisture. The sudden break in the curve indicates the fiber-saturation point, which was at 22.5 per cent moisture.

The fiber-saturation point reported here was obtained from electrical conductivity measurements made by the method introduced by Myer and Rees[3] and modified by Stamm ('29a). This method is known as the electro-conductivity

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[3] Myer and Rees. 1926. Cited by Stamm ('29a).

method. The results obtained by it are based upon the assumption that the specific conductance of the wood varies directly in proportion to the increase in moisture from the oven-dry condition to the fiber-saturation point, where it ceases to increase in proportion to additional moisture. Therefore, when the logarithm of the specific conductance was plotted against the percentage of moisture, a straight line was obtained up to the fiber-saturation point, where it broke sharply to a curve (fig. 2).

Measurements made by this method are subject to considerable error, and accordingly only averages of a great number of individuals are of any value. The most outstanding variables were polarization and moisture gradients caused by the presence of resins. Stamm ('29a) stated that "the effects of possible polarization were found to be negligible because of the extremely low conductance measured." In these experiments this was not found to be true; polarization was strong in all cases, even with the lowest possible currents. Differences in the lengths of the specimens used also caused considerable variation in the conductance, even though they were kept in sealed bottles for twelve hours or more. Accordingly, the specimens used were kept as close to 1 mm. in length as possible.

The fiber-saturation point of the three species of southern yellow pine studied in these experiments was found to lie in the neighborhood of 22.5 per cent moisture. When the averages of smaller groups of data were plotted independently the fiber-saturation point varied somewhat, and the best interpretation that could be given to these results was 22.5 ± 1 per cent moisture. This is within the range reported by Tiemann ('06, '07) and Wilson, Carlson and Luxford ('30), based upon bending and compression strengths.

The difference between species was well within the range of the individual variations of any given species, but a sufficiently large number of individual measurements on the separate species might show a consistent difference. This number would necessarily be very great and on resin-free wood.

MOISTURE CONTENT

The moisture content of the test specimens was determined from 1-in. sections cut between the bending and compression specimens, and from 2-in. samples cut from the compression specimens. These sections were weighed immediately after the test specimens were cut, dried to constant weight at 95–100° C., and reweighed. In very resinous specimens these determinations were subject to some error. Resinous materials tended to evaporate at temperatures around 100° C. and occasionally the liquid resin dripped from the specimens while in the oven.

Tests were made on material from four different conditions of moisture: material just as it came from the green log, material seasoned in an open-air shed, material cured in the relatively warm laboratory, and oven-dried material. Only the tests made on green material and that seasoned in the laboratory are reported here.

In trees 1 and 2 *(Pinus Taeda)*, tested in the lab.-dry condition, the material had been stored in the laboratory for about a year, so it was very dry and for the most part of a uniform moisture content. Tree 1 averaged 7.1 per cent moisture with a range from 6.0 to 8.8 per cent. Tree 2 averaged 7.3 per cent with a range from 5.5 to 11.1 per cent (table VI).

In the green material little variation was found in the moisture content of the heartwood in any one tree, regardless of position. There were only a few specimens in the heartwood of tree 4 that were in the range of the fiber-saturation point. (See strength tables VII and VIII for the moisture data.) The *average* moisture content of the entire section has no particular significance due to varying amounts of sapwood and the sharp differentiation of moisture in heart- and sapwood.

ABSOLUTE DENSITY OF THE WOOD SUBSTANCE

The absolute density of pine wood fiber as reported here is the weight of a unit volume of the resin-free wood substance in relation to the same volume of water at 4° C. Measurements were made on sawdust by the pycnometer method at a constant temperature of 30° C. The sawdust was taken from various positions in the tree and from each of the different species. It was first dried and treated for some time in benzol, which was kept warm in an oven, to extract the resin and other soluble compounds. The benzol was then removed with alcohol and the sawdust dried to constant weight at about 80° C. Next, it was boiled for some time in water, and a vacuum of about 25 cm. was applied at intervals to remove the air. This was continued until the air was replaced by water and the bottle reached a constant weight at 30° C. A range of values from 1.5156 to 1.5273 was found, with an average of 1.52 obtained by dropping the last two decimal places. The absolute density of southern yellow pine wood substance is thus given as 1.52.

Stamm ('29b) reported the density of *Pinus Taeda* as 1.531 (pycnometer method) when he used water, and 1.466 with benzol. Dunlop ('14) reported a density of 1.6197 for *Pinus palustris* by using acid and of 1.5060 with water, but since all of his results varied considerably he suggested 1.54 as a mean to represent in a rough way wood substance from all species.

PERCENTAGE OF RESIN

The percentage of benzol-soluble compounds designated as resins was determined by the loss of weight of oven-dried sawdust after soaking it for some days in benzol. The sawdust was taken from the compression and specific gravity specimens.

There was a certain relationship between the number of resin ducts and the percentage of resin, but no consistent correlation. The percentage of resin was greatest in the first 2 to 4 inches from the pith, often decreasing very sharply and then increasing again in the outer sapwood (tables VII and VIII). Resin was also abundant in and around injuries and knots, but it was often in localized areas where there was no sign of injury or knots and no increase in number or size of resin ducts. The percentages of resin reported here are in close agreement with the results given by Gomberg ('93), who made a more or less thorough study of the resin of *Pinus palustris* from Alabama.

SPECIFIC GRAVITY

The specific gravity was determined from 6-in. samples cut from between the bending and compression specimens in trees 1–5 and from 2-in. samples cut from the compression specimens in trees 6 and 7. There was less variation in the density-strength relations in the latter two trees. In the green material the samples were weighed in air and in water, dried to constant weight and reweighed. The specific gravity was calculated from the green volume and the oven-dry weight. The seasoned specimens were weighed in air and in water as above, but the sap pieces were reweighed in air, after being wiped off with a cloth, in order to determine the change in weight due to absorption of water while submerged.

It was found that sapwood specimens absorbed from 3 to 10 per cent of water during the process of weighing. It can readily be seen that the specific gravity thus obtained was subject to a certain amount of error. This error was diminished by reweighing but it may still be sufficient to affect the density-strength relations.

The presence of resin increased the specific gravity considerably, and where the resin was in localized areas or pockets the change in density was very sudden with no corresponding change in strength. In the case of very resinous material, the specific gravity was more than 0.1 too high, and in extreme cases more than 0.2. Only the corrected values were used in the interpretations of strength and structure in this paper.

Since the specific gravity of a particular specimen increased with a decrease in moisture, due to shrinkage below the fiber-saturation point, only specimens of about the same moisture content should be compared. Since the fiber ceased to expand with additional moisture above the fiber-saturation point, specific gravity values for green wood were especially comparable where they were corrected for resin.

The specific gravity in trees 1, 2, 3, 5, 6, and 7 decreased at a more or less uniform rate towards the top of the tree, whereas in tree 4 it fluctuated from bolt to bolt, reaching a maximum in bolt *c*, decreasing considerably in bolt *d*, and again increasing through bolts *e* and *f*.

In trees 1, 2, and 7 the specific gravity increased from the pith to the bark, whereas in trees 3, 4, and 6 the increase extended over only the first 2 to 3 inches after which there was a decrease towards the periphery. This condition was due to the very slow growth of the latter trees. In tree 3, however, this relation changed. The first samples around the pith had the greatest density in the lower bolts, whereas the intermediate or outer specimens were the heaviest in bolt *h*. In tree 5 the specific gravity increased from the pith to a maximum in the outer part of the heartwood and decreased from this point towards the bark.

The maximum and minimum specific gravity for the bolt rarely occurred on the same side of the tree. In trees 1, 2, 3, and 4 the greatest density was usually found in the closer-ringed material, whereas in tree 5 it was found in the medium- to broad-ringed material. In the latter case, however, the narrow-ringed material was found on the outer portion of the tree, and it is indicated that in general the tracheid length and density reached a maximum at about the same time (between 40 and 100 years), which varied somewhat with the growth rate of the tree. The material from the first 30 to 40 rings and the outer sapwood of the older trees was lighter in all cases than the material laid down during the 40- to 100-year period. It is evident that the rate of growth and age of the tree are the controlling factors determining the position of greatest density in the cross-section of a given tree.

Structural Properties

RATE OF GROWTH

By observing the relative number of growth rings per inch it was found that the material represented in this study divided itself into three natural divisions: trees 1, 2, and 7 *(Pinus Taeda)* of very rapid growth, tree 5 *(Pinus Taeda)* and tree 3 *(Pinus echinata)* of medium growth, and trees 4 and 6 *(Pinus palustris)* of very slow growth (table I).

Trees 1, 2, and 7 grew more than three times as fast as trees 4 and 6 and twice as fast as tree 3. Therefore, the first test

TABLE I

FIELD NOTES FOR THE SEVEN TREES STUDIED

	Tree 1 *P. Taeda*	Tree 2 *P. Taeda*	Tree 5 *P. Taeda*	Tree 7 *P. Taeda*	Tree 3 *P. echinata*	Tree 4 *P. palustris*	Tree 6 *P. palustris*
Where grown	Near Tylertown, Miss.	Near Tylertown, Miss.	About 8 mi. west of Sandy Hook, Miss., near La. border	In Tylertown, Miss.	Near Tylertown, Miss.	Near Tylertown, Miss.	Near Tylertown, Miss.
Approximate elevation	225 ft.	250 ft.	225 ft.	———	265 ft.	300 ft.	———
Soil conditions	Moderately dry clay loam	Set clay loam	Moist sandy clay	Sandy clay top soil, red clay sub-soil	Dry sandy clay	Dry sandy clay	Sandy clay top soil, red clay sub-soil
Exposure	West slope	Flat	Flat	Gentle south slope	Steep northwest slope	Steep southwest slope	Gentle north slope
Stand of timber	Dense second growth in old field	Moderately dense original swamp growth	Dense original hard wood with scattered pine trees	Open second growth hard and soft wood	Moderately dense original growth recently cut over, leaving open stand	Dense original growth recently cut over	Open second growth recently cut over
Height of tree	93 ft.	85 ft.	135 ft.	98 ft.	75 ft.	75 ft.	82 ft.
Diameter under bark at butt	18 in. (7 in. from ground)	18½ in. (30 in. from ground)	43 in.	19½ in.	17¾ in. (10 in. from ground)	16½ in. (10 in. from ground)	17½ in.
Approximate age	50 yrs.	50 yrs.	160 yrs.	60 yrs.	100 yrs.	160 yrs.	160 yrs.
Rate of growth	Rapid	Rapid	Medium to rapid except for very slow growing outer 4 or 5 in.	Rapid	Moderately slow	Very slow	Very slow
Date of cutting	Oct. 4, 1930	Oct. 4, 1930	Oct. 2, 1931	Feb. 1, 1933	Oct. 4, 1930	Oct. 4, 1930	Dec. 6, 1932

specimens near the pith of trees 1 and 2 represented only three to four years' growth, those of tree 5, six to fourteen, while there were more rings in some of the first specimens of tree 4 and especially tree 6 than there were in the entire cross-sections of trees 1, 2, and 7 (pl. 9). Trees 4 and 6 had from 10 to 44 rings per inch. This would give from 15 to 66 growth rings for each 1½ x 1½-in. specimen. Since the growth was not uniformly slow throughout the entire cross-section, there were few test specimens that contained more than 50 growth rings. The number of rings per inch is given in tables VII and VIII.

Trees 1, 2, 5, and 7 *(Pinus Taeda)* were more or less symmetrical in outline with the pith near the center, thus giving approximately the same number of test specimens on each side. Accordingly, there was little difference in the number of rings per inch at a given distance from the pith either on the opposite sides or at different levels.

Tree 3 *(Pinus echinata)* was slightly crooked and asymmetrical. The pith was nearer the bark on the south and west sides at the butt, whereas it was near the center of the log in bolt *h* at about 30 feet from the ground. The rings on the narrow side were necessarily closer, and since the pith was not straight it was impossible to cut an equal number of the specimens on each of the four sides. The growth was somewhat more rapid through the second and sometimes the third specimen in the lower bolts, and averaged about 8 rings per inch, but out near the bark, especially on the south and west sides, the growth decreased rapidly, giving about 15 to 20 rings per inch.

Trees 4 and 6 *(Pinus palustris)* were also crooked, with the pith off center. The *h* bolt in tree 4 and the *a* bolt in tree 6 were asymmetrical. Trees 4 and 6 had only two or three medium-width rings around the pith, after which the growth was extremely slow in the first 2 to 3 inches, except for a very few rings which occurred in scattered groups. The growth was somewhat more rapid in the outer part of the heartwood and in the sapwood towards the top of the tree.

These trees were characterized by periods of alternately slow and more rapid growth. While the entire tree would be considered to have slow growth, the rate changed at intervals from about 20 rings per inch to more than 40 rings and back to 15 or 20 without following any particular pattern. Moreover, the width of ring varied greatly on opposite sides of the tree. Therefore, pieces taken at a given distance from the pith on opposite sides were not always matched specimens; one specimen may have been formed as much as forty years after the other. The broader rings often contained a certain amount of compression wood.

SUMMER WOOD

The percentage of summer wood was estimated macroscopically when the specimens were measured for testing. In the samples in which the resin ducts and shape of fiber were studied, the summer wood was measured under the microscope. Since in general the estimated values were found to be either too high, as in the specimens containing more than 50 per cent summer wood, or too low, only the percentage of summer wood obtained by microscopic measurements are reported here.

The first 2 to 5 rings of the tree usually contained very little summer wood. There was no sharp demarcation between early and late wood, and it was not uncommon for the first ring to be entirely without thick-walled cells such as were found in the summer wood farther from the pith. One was compelled to set an arbitrary limit on the spring and summer wood in such cases, since the cells were progressively smaller and thicker-walled towards the outer part of the ring. In some trees poor differentiation occasionally occurred in annual rings far from the pith. This was particularly noticeable in trees 1 and 2 *(Pinus Taeda)* where a large percentage of compression wood was found.

In the young rapid-growth trees 1, 2, and 7 *(Pinus Taeda),* the percentage of summer wood increased from the pith to the periphery whereas in the older and slower-growing trees 3 *(Pinus echinata),* 4 and 6 *(Pinus palustris),* and 5 *(Pinus Taeda)* it reached a maximum some distance from the bark and then decreased. (Mohr and Roth, '97, found this to be true of all old trees.) In the close-ringed trees a maximum of summer wood was often reached within the first 2 to 3 inches of the pith, with little variation over the rest of the cross-section.

The percentage of summer wood varied a great deal with height in the tree. Trees 1 and 2, representing vigorous-growth *Pinus Taeda,* averaged nearly twice as much summer wood at the butt as at a point 30 feet higher. In the slower-growing trees 3 *(Pinus echinata)* and 6 *(Pinus palustris),* the decrease was not so rapid, and in tree 4 *(Pinus palustris),* the percentage of summer wood decreased progressively but not uniformly from butt to top.

The "average" percentage of summer wood may be misleading in rapid-growth trees, since in a given cross-section considerable areas near the pith had as little as 15 per cent summer wood whereas only a few inches farther out there was often 60 per cent or more. Furthermore, the density of summer wood varied in the individual trees and particularly in trees of different species, as will be discussed in detail later.

SIZE AND DISTRIBUTION OF THE RESIN DUCTS

Resin ducts are canal-like intercellular spaces surrounded by parenchyma cells. The cells immediately around them, known as epithelial cells, were thin-walled and were more or less equilateral. The succeeding cells radiating from the resin ducts had increasingly thicker walls and became elongated until they blended into the tracheids. It was not uncommon for septate tracheids to occur in this transition zone.

Table II shows the size and distribution of the resin ducts both as to height and to distance from the pith in the tree. The samples for study were taken from the specimens used for the compression tests.

There was no attempt to determine the lengths of the longitudinal resin ducts which were distributed throughout the xylem. They were more abundant immediately around the pith, especially in the first 5-10 annual rings. The first ring often contained as many as 500 resin ducts, while farther out towards the periphery of the stem they were most numerous in the regions of transition from spring to summer wood and

TABLE II

THE SIZE AND DISTRIBUTION OF THE RESIN DUCTS AND THE PERCENTAGE OF AREA OCCUPIED BY THEM. THE PERCENTAGE OF SUMMER WOOD IS GIVEN IN TABLES VII AND VIII

Specimen	Number of resin ducts per sq. cm.		Mean diameter in mm.	Percentage of area of cross-section
	spring wood	summer wood		
Tree 1—*Pinus Taeda* (loblolly pine)				
1aN2	33	64	0.20	1.32
1aN4	6	79	0.22	1.61
1aN6	1	58	0.23	1.68
1aN7	2	48		1.62
1aN8	2	54	0.24	1.89
1dN2	43	52	0.19	1.25
1dN4	2	70	0.21	1.10
1dN6	0	55	0.23	1.05
1hN2	34	86	0.20	1.26
1hN4	41	63	0.22	1.82
1hN6	6	72	0.23	1.24
Tree 2—*Pinus Taeda* (loblolly pine)				
2aN2	54	71	0.20	1.86
2aN4	34	70	0.22	2.08
2aN5	25	50		1.65
2aN6	15	42	0.23	1.32
2aN8	8	47	0.24	1.47
2dN1	54	85		2.05
2dN2	38	57	0.21	1.51
2dN4	26	51	0.23	1.58
2dN5	28	45		1.61
2dN6	23	39	0.24	1.40
2dN8	17	43	0.25	1.47
2hN1	69	85		2.50
2hN2	34	58	0.21	1.34
2hN3	35	72		1.85
2hN4	38	60	0.23	1.85
2hN5	36	58		1.95
2hN6	35	43	0.24	1.71
2hN8	27	49	0.24	1.70
Tree 5—*Pinus Taeda* (loblolly pine)				
5bN1	45	55	0.19	1.53
5bN3	53	21	0.20	1.13
5bN5	53	20	0.21	1.13
5bN7	50	37	0.23	1.74
5bN9	46	43	0.23	1.83
5bN11	40	29	0.23	1.37
5bN13	8	48	0.22	1.23
5bN15	17	54	0.21	1.27

TABLE II (Continued)

Specimen	Number of resin ducts per sq. cm.		Mean diameter in mm.	Percentage of area of cross-section
	spring wood	summer wood		
Tree 5 (Continued)				
5iN1	40	72	0.19	1.31
5iN3	29	42	0.21	1.14
5iN5	15	52	0.22	1.17
5iN7	29	28	0.23	1.19
5iN9	20	43	0.23	1.22
5iN11	9	39	0.23	0.92
5iN13	17	95	0.22	1.67
5qN1	40	52	0.19	1.19
5qN3	33	37	0.20	1.18
5qN5	27	46	0.21	1.12
5qN7	23	57	0.23	1.42
5qN9	9	75	0.23	1.25
5qN11	17	106	0.22	1.61
Tree 7—*Pinus Taeda* (loblolly pine)				
7aN1	17	76	0.20	1.12
7aN3	21	50	0.22	1.20
7aN5	21	34	0.25	1.29
7aN7	13	38	0.25	1.25
7gN1	21	44	0.21	1.03
7gN3	20	41	0.22	1.07
7gN5	11	48	0.23	1.12
7gS7	16	52	0.23	1.31
7mN1	23	35	0.21	0.92
7mN3	9	58	0.23	1.18
7mN5	11	51	0.24	1.37
7mS7	16	50	0.23	1.29
Tree 3—*Pinus echinata* (shortleaf pine)				
3aN1	18	30	0.19	0.69
3aN2	38	48		1.24
3aN3	23	19	0.20	0.66
3aN4	24	22		0.72
3aN5	33	26	0.20	0.91
3aN6	15	28		0.73
3aN7	30	28	0.21	1.00
3aN8	19	22		0.71
3aN9	30	26	0.21	1.00
3aN10	30	26		0.97
3dN1	24	43	0.19	0.89
3dN3	23	22	0.20	0.71
3dN5	29	30	0.20	0.92
3dN7	19	21	0.21	0.69

TABLE II (Continued)

Specimen	Number of resin ducts per sq. cm.		Mean diameter in mm.	Percentage of area of cross-section
	spring wood	summer wood		
Tree 3 (Continued)				
3hN1	22	32	0.19	0.70
3hN2	22	49		0.89
3hN3	15	20	0.20	0.52
3hN5	20	15	0.20	0.57
Tree 4—*Pinus palustris* (longleaf pine)				
4aN2	19	67	0.19	1.07
4aN4	27	45	0.20	1.10
4aN6	27	45	0.21	1.21
4aN8	37	39	0.22	1.34
4cN1	27	67	0.20	1.08
4cN2	35	69		1.22
4cN3	27	63	0.21	1.27
4cN5	36	34	0.22	1.17
4hN1	33	23	0.19	1.15
4hN2	25	44		0.85
4hN3	28	49	0.22	1.06
4hN4	26	47		0.96
Tree 6—*Pinus palustris* (longleaf pine)				
6aN1	18	78	0.20	1.45
6aN3	14	31	0.23	0.90
6aN5	29	50	0.25	1.82
6aS7	22	41	0.25	1.41
6eN1	43	92	0.20	1.69
6eN3	27	62	0.22	1.51
6eN5	20	56	0.23	1.32
6iN1	38	53	0.20	1.32
6iN3	24	45	0.22	1.07
6iN5	33	47	0.24	1.65

in the summer wood, with very few in the first part of the spring wood. This was particularly noticeable in the broad-ringed material (pl. 10, fig. 1). Resin ducts were often aggregated in false rings and occasionally formed a definite band near the middle of the spring wood rings. In narrow-ringed material the resin ducts were scattered promiscuously throughout the annual ring, but, with the exception of certain specimens in *Pinus echinata,* they were more numerous in the summer-wood portion.

The mean diameter of the resin ducts increased from the pith towards the periphery of the stem, reaching a maximum near the outer sap-wood, but occasionally it decreased slightly in the last-formed rings in the older trees. The greater number of resin ducts in the first and last rings was quite marked in tree 5.

The percentage of cross-sectional area taken up by resin ducts was slightly greater in the rapid-growth *Pinus Taeda* than in the other species. In *Pinus Taeda* the area taken up by them increased in the summer-wood portion of the ring towards the periphery of the stem and decreased markedly in the spring wood in the same direction, whereas in *Pinus palustris* and in *Pinus echinata* there was no consistent change. In *Pinus echinata* the resin ducts were smaller and fewer in number than in the other species. On the whole there was less than 1 per cent of the cross-sectional area taken up by them. In the summer wood of *Pinus palustris* and *Pinus Taeda,* however, it was not uncommon for more than 2 per cent, and for small areas as much as 3 per cent, of the area to be occupied by resin ducts.

In general, the mean diameter of the resin ducts was slightly greater in the spring wood than in the summer wood, although the diameters in the tangential direction were frequently greater in the summer wood, where the resin ducts were often aggregated in rows of from 2 to 5 (pl. 10, fig. 2). This was particularly true of *Pinus Taeda,* where the aggregations were occasionally about 1 mm. in width. Such groups also occurred in the spring wood but they were much less common. In no instance was there any evidence of injury in the vicinity of these groups of resin ducts.

There was no consistent relationship between the number of resin ducts and the height of the tree. However, as a whole the mean diameters of the resin ducts, and thus the area taken up by them, were greatest in the lower bolts. They decreased slightly through the middle portion of the tree and usually increased again near the top. This condition, however, was often reversed in individual specimens from the outer portion of the tree.

Areas of parenchyma cells occurred, other than those around the resin ducts, which areas contained secretory or resin cells. The greater number of them were thick-walled. These areas of parenchyma cells were more common in the spring wood and occurred in all three species.

SIZE AND DISTRIBUTION OF THE WOOD RAYS

The significance of the wood rays in relation to the structure and strength of wood attracted the attention of Nördlinger ('60), and in 1881 he published his findings on the number of rays per mm. for a number of hard woods and noted the numerous small rays in the conifers.

Essner ('82) studied the distribution and height of the rays in various species of conifers. He found little or no difference in the number of rays on the narrow side of trees caused by unequal growth rate, but did observe that certain specimens of *Cupressus sempervirens* of symmetrical growth had 83 rays per mm. on one side as compared with 62 on the opposite side. The height of the rays increased from the pith to the bark.

Jaccard ('15) studied the rays at the various levels in the tree and in the branches of *Sequoia* and *Picea*. In the main stem or trunk the rays decreased in number from a maximum at the base to a minimum within the lower part of the trunk and again increased towards the top of the tree. They were more numerous but smaller in the branches where the greatest number was found in the areas of compression wood on the lower side. He observed that as the rays decreased in number the tracheids increased in size. Myer ('22) reported the ray volumes of a large number of American woods and pointed out that the hard woods had a much greater ray volume than the conifers, an average of 17.04 and 7.08 per cent, respectively. The ray volumes for the southern pines were 7.63 per cent for *Pinus Taeda*, 8.05 per cent for *Pinus echinata*, and 8.30 per cent for *Pinus palustris*. In summarizing his results, Myer ('30) stated that the ray volume of white pine, hemlock, and sugar maple was greatest at the top of the merchantable log and second greatest at the stump level, while a reduction was found at the 16-ft. level. His observations as recorded in the paper, however, show the maximum at the stump level. If the latter is the correct conclusion, it agrees with other work. There was no consistent relationship between the ray volume and the different sites from which the trees were cut. The ray height in the sugar maple was least at the stump level but its width was greatest at this point. Myer's ('30) observations on the effects of the site do not agree entirely with those of Hartig ('01) on the oak. The latter found a greater ray volume in the plants grown in the open and an increase in ray volume if shaded plants were suddenly given full illumination. Forsaith ('20) found a reduction of rays in certain alpine forms, and Shope ('27) found that the size of the ray cells, as well as other cells, increased in the aspen at higher elevations. Harlow ('27) was unable to find any consistent variations in the ray volume of plants from different sites. He observed, however, that it was greater at the base of the tree. There was a great variation in the size, type, and distribution of rays in the different species of hard woods, depending upon their ages, according to Zache ('86), Hartig ('94), and Eames ('10).

It is evident that there is not sufficient data to draw any reliable conclusions as to the size and distribution of wood rays due to environmental conditions or their effects on strength, but it is universally agreed that the ray volume of conifers is greatest in the butt of the tree and least in the main trunk at a height of 20 to 40 feet.

In this investigation the wood rays of southern pine were found to be largely of the linear (uniseriate) and fusiform (multiseriate) types. The latter contained solitary lateral resin ducts. Occasional biseriate rays were observed, but these were rare and of little significance in this study. The area of the rays was determined by taking two-thirds of the area of a circumscribed parallelogram based upon the mean height and breadth of the rays in a given specimen.

The study was made on tangential sections mounted in Canada balsam, and the measurements were made by means of a micrometer eyepiece. The number per mm. was determined by taking the average from 100 to 400 sq. mm. This was made possible by using a cover glass on which fine lines were etched at a distance of about 0.8 mm. The number of rays between the lines could be accurately counted for the entire area of a large section, since the lines were sufficiently transparent to allow the counting of rays beneath them.

Fusiform Rays.—The width (lateral diameter), the height (longitudinal diameter), the distribution of the fusiform rays, and the percentage of area occupied by them is given in table III. The width of these rays varied from about 0.05 mm. to about 0.08 mm. They were smaller near the pith and reached a maximum near the periphery of the stem. There was little difference in the breadth of the rays in the different species. The height of the fusiform rays, in most specimens, tended to decrease from the butt of the tree towards the top, reaching a minimum through the middle portion of the tree. In tree 7 *(Pinus Taeda),* however, it increased slightly from the base to the top.

The fusiform rays were more or less constant in number at the different heights in the tree, but they decreased very markedly from the pith towards the periphery of the stem at all levels studied. However, since the number per unit area often varied more than 100 per cent in local areas, it was necessary to study a number of sq. cm. in order to get a reliable average. In 1aN6 (table III) there was an average of 83 fusiform rays per sq. cm., and in certain sections taken at this point there were more than 100 per sq. cm.

Fusiform rays were more abundant in *Pinus Taeda* than in either *Pinus palustris* or *Pinus echinata,* but there was no pronounced difference in the height of these rays in either species. There was no indication of a fixed pattern or sequence of occurrence in any of the species. They were scattered throughout, but occurred occasionally in groups.

Linear Rays.—The linear rays were very numerous in the first growth ring, where there were from 70 to 120 minute rays per sq. mm. immediately adjacent to the pith. They were

TABLE III

THE SIZE AND DISTRIBUTION OF THE FUSIFORM RAYS

Specimen	Approximate number of rings from the pith	Number of rays per sq. cm.*	Mean width in mm.	Mean height in mm.	Percentage of area occupied by fusiform rays
Tree 1—*Pinus Taeda* (loblolly pine)					
1aN2	3	71	0.061	0.343	0.99
1aN4	16	50	0.063	0.436	1.02
1aN6	34	83	0.068	0.428	1.61
1aN8	45	38	0.075	0.521	0.99
Ave.		60	0.066	0.432	1.15
1dN2	3	76	0.060	0.350	1.25
1dN4	13	50	0.059	0.422	0.84
1dN6	30	47	0.062	0.422	0.82
1dN8	40	45	0.073	0.504	1.10
Ave.		55	0.063	0.425	1.00
1hN2	3	43	0.062	0.359	0.64
1hN4	11	38	0.067	0.398	0.72
1hN6	25	38	0.070	0.500	0.89
Ave.		40	0.066	0.419	0.75
Tree 2—*Pinus Taeda* (loblolly pine)					
2aN2	3	57	0.060	0.328	0.75
2aN4	10	38	0.063	0.462	0.73
2aN6	20	30	0.072	0.537	0.78
2aN8	35	31	0.066	0.514	0.70
Ave.		39	0.065	0.460	0.74
2dN2	3	56	0.078	0.393	0.77
2dN4	10	35	0.055	0.410	0.54
2dN6	19	39	0.058	0.400	0.60
2dN8	30	31	0.066	0.500	0.67
Ave.		40	0.062	0.427	0.65
2hN2	3	59	0.055	0.250	0.76
2hN4	10	38	0.067	0.379	0.65
2hN6	17	35	0.063	0.470	0.73
2hN8	28	30	0.067	0.484	0.65
Ave.		41	0.063	0.396	0.70

* Note that the number of fusiform rays is given in sq. cm.

TABLE III (Continued)

Specimen	Approximate number of rings from the pith	Number of rays per sq. cm.*	Mean width in mm.	Mean height in mm.	Percentage of area occupied by fusiform rays
Tree 5—*Pinus Taeda* (loblolly pine)					
5bN1	10	54	0.063	0.328	0.75
5bN7	46	37	0.076	0.487	0.91
5bN1–5	125	26	0.075	0.744	0.97
Ave.		39	0.071	0.519	0.87
5iN1	6	67	0.065	0.312	0.91
5iN7	40	34	0.077	0.434	0.74
5iN13	105	28	0.069	0.577	0.74
Ave.		43	0.070	0.441	0.79
5qN1	4	58	0.057	0.288	0.63
5qN5	27	39	0.068	0.488	0.86
5qN11	88	34	0.073	0.522	0.86
Ave.		44	0.066	0.433	0.78
Tree 7—*Pinus Taeda* (loblolly pine)					
7aN1	5	56	0.059	0.330	0.73
7aN3	15	43	0.065	0.368	0.69
7aN5	26	37	0.084	0.373	0.77
7aN7	40	35	0.085	0.402	0.79
7aN9	50	34	0.067	0.414	0.63
Ave.		41	0.072	0.377	0.72
7gN1	4	46	0.056	0.367	0.63
7gN3	13	42	0.061	0.372	0.63
7gN5	25	38	0.063	0.371	0.59
7gN7	39	38	0.058	0.410	0.60
Ave.		41	0.059	0.380	0.61
7mN1	4	62	0.064	0.321	0.85
7mN3	13	50	0.066	0.423	0.93
7mN5	26	43	0.067	0.459	0.88
7mN7	40	45	0.066	0.485	0.89
Ave.		50	0.066	0.422	0.89

* Note that the number of fusiform rays is given in sq. cm.

TABLE III (Continued)

Specimen	Approximate number of rings from the pith	Number of rays per sq. cm.*	Mean width in mm.	Mean height in mm.	Percentage of area occupied by fusiform rays
Tree 3—*Pinus echinata* (shortleaf pine)					
3aN1	12	32	0.057	0.474	0.57
3aN3	35	43	0.059	0.485	0.82
3aN5	59	33	0.061	0.497	0.67
3aN7	84	32	0.065	0.532	0.74
3aN9	108	28	0.068	0.550	0.70
Ave.		36	0.062	0.507	0.70
3dN1	16	30	0.057	0.400	0.46
3dN3	44	28	0.059	0.430	0.47
3dN5	70	28	0.063	0.482	0.57
3dN7	98	27	0.068	0.504	0.61
Ave.		28	0.062	0.454	0.53
3hN1	12	44	0.057	0.370	0.63
3hN3	35	28	0.063	0.389	0.46
3hN5	61	27	0.068	0.410	0.50
Ave.		33	0.062	0.389	0.53
Tree 4—*Pinus palustris* (longleaf pine)					
4aN2	36	43	0.054	0.335	0.52
4aN6	122	31	0.063	0.474	0.67
4aN8	150	31	0.071	0.614	0.90
Ave.		36	0.062	0.474	0.66
4dN1	40	39	0.061	0.441	0.71
4dN3	103	33	0.068	0.497	0.74
4dN5	145	28	0.073	0.543	0.69
Ave.		33	0.067	0.493	0.71
4hN1	21	36	0.068	0.368	0.50
4hN3	67	30	0.071	0.428	0.61
4hN5	110	30	0.075	0.489	0.73
Ave.		32	0.071	0.425	0.65

* Note that the number of fusiform rays is given in sq. cm.

TABLE III (Continued)

Specimen	Approximate number of rings from the pith	Number of rays per sq. cm.*	Mean width in mm.	Mean height in mm.	Percentage of area occupied by fusiform rays
Tree 6—*Pinus palustris* (longleaf pine)					
6aN1	43	31	0.056	0.372	0.35
6aN3	67	26	0.066	0.389	0.48
6aN5	106	27	0.070	0.480	0.62
6aN7	142	28	0.072	0.480	0.65
Ave.		28	0.066	0.430	0.52
6eN1	25	28	0.053	0.348	0.34
6eN3	75	33	0.057	0.427	0.52
6eN5	115	25	0.069	0.406	0.46
Ave.		29	0.060	0.394	0.44
6iN1	28	30	0.059	0.342	0.42
6iN3	72	28	0.071	0.415	0.57
6iN5	112	28	0.066	0.474	0.61
Ave.		29	0.065	0.410	0.53

* Note that the number of fusiform rays is given in sq. cm.

naturally very small at this point, being only about 0.08 mm. or less in height. As the stem increased in diameter the rays were separated more and more, new ones originating with the additional tiers of tracheids. Since the number of rays did not increase so rapidly as the diameter of the stem, there was only about one-fourth to one-sixth as many rays per sq. mm. in the outer portion as near the pith.

The decrease in number of rays was not uniform in all specimens nor all portions of a given specimen. At certain areas in the tree marked only by a sudden change in growth rate, there was a temporary increase in number of rays which was followed by the usual rate of decline.

Table IV gives the number of linear rays per sq. mm., their mean heights and breadths, and the approximate area taken up by them in the different portions of the tree as indicated. Since the size of the rays often increased more rapidly than the number decreased, in many bolts the area occupied by them was greatest in the outer portion of the tree. This was true of all three species studied.

The breadth of the rays increased centrifugally only slightly, from about 0.022 to 0.028 mm. The height increased more or less rapidly, attaining an average of more than 0.2 mm. in certain trees, although individual rays were occasionally 1 mm. or more in height in *Pinus Taeda.*

The number of rays was practically constant for a given area at different heights in the tree, except in the butt where there were a few more. Their breadth was also reasonably uniform throughout the tree, but the height decreased slightly from the stump level through the middle portion of the trunk, with a second maximum in the region of the crown. For this reason the area taken up by the rays was greatest at the base and least at about the 30- to 40-ft. level.

The linear rays, like the fusiform, were more numerous at a given distance from the pith and slightly larger in the specimens of *Pinus Taeda* than in either *Pinus palustris* or *Pinus echinata,* the latter of which had fewer and smaller rays. If, however, the age of the tree were taken into consideration, *Pinus echinata* and *Pinus palustris* had a greater number of rays than did *Pinus Taeda* due to the narrow rings near the pith.

Tables VII and VIII show that *Pinus echinata* had a lower percentage of area occupied by resin ducts and wood rays than *Pinus palustris,* and that *Pinus Taeda* had a greater percentage than the other two. It was unfortunate that there was only one tree of *Pinus echinata* available for study, since there were certain variations shown in the different trees of the other two species. Furthermore, tree 3 grew on a north slope where it was probably shaded a good part of the time, which, according to Hartig's ('01) observations, would account for the smaller number of rays.

There were only slight variations in number or size of linear rays on opposite sides of a given tree, but areas containing a large amount of compression wood had somewhat broader rays and a greater number of both fusiform and linear rays, which increased the ray volume somewhat.

TABLE IV

THE SIZE AND DISTRIBUTION OF THE LINEAR RAYS

Specimen	Appoximate number of rings from the pith	Number of rays per sq. mm.	Mean width in mm.	Mean height in mm.	Percentage of area occupied by linear rays
Tree 1—*Pinus Taeda* (loblolly pine)					
1aN1	3	32	0.023	0.161	7.93
1aN3	16	29	0.024	0.168	7.80
1aN5	34	28	0.025	0.182	7.80
1aN7	45	28	0.026	0.191	9.26
1dN1	3	30	0.022	0.172	8.10
1dN3	13	25	0.023	0.174	7.10
1dN5	30	24	0.025	0.186	7.50
1dN7	40	22	0.026	0.190	7.50
1hN1	3	26	0.023	0.180	7.35
1hN3	11	24	0.026	0.182	7.13
1hN5	25	22	0.026	0.190	7.14
Tree 2—*Pinus Taeda* (loblolly pine)					
2aN1	3	30	0.024	0.167	8.00
2aN3	10	27	0.026	0.170	7.93
2aN5	20	26	0.026	0.204	9.20
2aN7	35	25	0.027	0.194	8.72
2dN1	3	29	0.024	0.159	7.25
2dN3	10	27	0.025	0.165	7.27
2dN5	19	26	0.026	0.184	8.05
2dN7	30	25	0.027	0.198	8.92
2hN1	3	30	0.025	0.161	7.60
2hN3	10	27	0.026	0.164	7.23
2hN5	17	25	0.026	0.169	7.12
2hN7	28	24	0.027	0.207	9.10
Tree 5—*Pinus Taeda* (loblolly pine)					
5bN1	10	28	0.022	0.160	6.15
5bN7	46	24	0.025	0.186	7.60
5bN15	125	20	0.025	0.244	8.75
5iN1	6	26	0.022	0.150	5.43
5iN7	40	23	0.024	0.170	7.02
5iN13	105	20	0.026	0.194	7.00
5qN1	4	25	0.023	0.160	5.55
5qN5	27	23	0.026	0.200	9.74
5qN11	88	22	0.025	0.198	7.20

TABLE IV (Continued)

Specimen	Appoximate number of rings from the pith	Number of rays per sq. mm.	Mean width in mm.	Mean height in mm.	Percentage of area occupied by linear rays
Tree 7—*Pinus Taeda* (loblolly pine)					
7aN1	5	31	0.023	0.155	7.25
7aN3	15	30	0.023	0.168	8.37
7aN5	26	29	0.024	0.171	8.17
7aN7	40	25	0.024	0.173	7.02
7aN9	56	26	0.024	0.162	6.90
7gN1	4	30	0.023	0.141	6.46
7gN3	13	27	0.023	0.158	6.45
7gN5	25	26	0.024	0.153	6.54
7gN7	39	28	0.024	0.127	5.74
7mN1	4	30	0.023	0.149	6.65
7mN3	13	28	0.024	0.151	6.67
7mN5	26	27	0.024	0.150	6.55
7mN7	40	29	0.024	0.151	7.15
Tree 3—*Pinus echinata* (shortleaf pine)					
3aN1	12	25	0.023	0.145	5.30
3aN3	35	24	0.023	0.148	5.44
3aN5	59	23	0.023	0.153	5.37
3aN7	84	22	0.024	0.160	5.63
3aN9	108	21	0.025	0.166	5.80
3dN1	16	25	0.022	0.140	5.14
3dN3	44	24	0.023	0.145	5.35
3dN5	70	23	0.024	0.157	5.76
3dN7	98	22	0.024	0.160	5.62
3hN1	12	26	0.022	0.143	5.45
3hN3	35	24	0.023	0.149	5.50
3hN5	61	21	0.024	0.158	5.31
Tree 4—*Pinus palustris* (longleaf pine)					
4aN2	36	24	0.023	0.151	5.94
4aN6	122	24	0.024	0.159	6.50
4aN8	150	23	0.026	0.167	7.05
4dN1	40	25	0.024	0.152	5.95
4dN3	103	24	0.024	0.154	6.04
4dN5	145	23	0.026	0.158	6.11
4hN1	21	24	0.023	0.148	5.30
4hN3	67	24	0.024	0.151	5.47
4hN5	110	23	0.024	0.152	5.60

TABLE IV (Continued)

Specimen	Appoximate number of rings from the pith	Number of rays per sq. mm.	Mean width in mm.	Mean height in mm.	Percentage of area occupied by linear rays
Tree 6—*Pinus palustris* (longleaf pine)					
6aN1	43	28	0.022	0.141	5.79
6aN3	67	25	0.023	0.154	5.90
6aN5	106	23	0.024	0.208	7.64
6aN7	142	23	0.025	0.195	7.46
6eN1	25	27	0.021	0.145	5.45
6eN3	75	24	0.022	0.145	5.18
6eN5	115	23	0.024	0.168	6.50
6iN1	28	25	0.021	0.143	5.61
6iN3	72	24	0.023	0.159	5.76
6iN5	112	23	0.024	0.202	7.80

TRACHEID DIMENSIONS

The length of the tracheids in coniferous wood varies with the age of the tree at the time the cells are formed. Sanio ('72) found that in *Pinus sylvestris* the tracheids increased in length from the first ring to a maximum in the 45th ring, after which they remained constant. This led him to believe that the size of the cell had a fixed relationship to the age of the tree, but this has been proved untrue. Mell ('10) observed that the wood fibers were longest, for any given annual ring, in rapid-growth trees. Bailey and Shepard ('15) noted that in certain species of conifers the length of the tracheids increased from the inner portion of the secondary xylem up to a certain age, after which it fluctuated. No constant length of tracheids was found. In addition, Gerry ('15) found that the fiber length increased from the butt towards the crown for about two-thirds of the height of the tree. The longest fibers in a given ring were in the first spring-wood cells and the shortest in the last summer-wood cells. Gerry ('16), contrary to Mell, was not able to find any correlation between fiber length and rate of growth in Douglas fir, but noted a rapid increase in all dimensions of the fiber in the first twenty years of growth. Lee and Smith ('16), on the other hand, found that in Douglas fir the longest fibers in a given ring were in the summer wood. Further study on the fiber length of different species was made by Bailey and Tupper ('18), Kribs ('28), and Gerry ('29). MacMillan ('25) found that there was a greater percentage of short fiber in red spruce grown under suppressed conditions than in that grown in free, which agrees with the findings of Mell.

In this study, the tracheids were prepared for measuring by first macerating them (Jeffrey method) and then teasing them apart on the stage of a compound microscope. Measurements were made by means of a micrometer eye-piece. Each figure shown in tables vii and viii is the average of 200–500 tracheids.

The tracheids were very short in the first ring around the pith, with an average length of 1.5 mm. or less. Their length increased rapidly through the first 5 to 10 rings and more gradually for the remainder of the growth of the tree or at least until the tree reached the age of 100 years or more. No maximum length was determined in this material.

In a given tree the length of the tracheids was dependent upon the number of years of growth and not upon the distance from the pith; therefore, in broad-ringed material they were shorter at a given distance from the pith than in the narrow-ringed material. This was very outstanding in the different trees used in this study. In trees 1, 2, and 7, and somewhat in tree 5 (all *Pinus Taeda*), the rings were broad near the pith and for some distance out, whereas in tree 3 *(Pinus echinata)* and particularly in trees 4 and 6 *(Pinus palustris)* the rings were very narrow. Consequently, the average length of the tracheids in the first test specimen near the pith in trees 3, 4, and 6 was as great as it was in the second or third specimen from the pith in trees 1, 2, 5, and 7. The tracheids representing approximately the same year's growth were slightly longer in the rapid-growth *Pinus Taeda* than in the other species.

At the successively higher levels in the tree, the tracheids increased in length more rapidly from the pith to the bark. The result was that the average length for the cross-section tended to increase towards the top of the tree. The tracheids in a given ring increased in length towards the top, especially for the first few feet from the butt.

Groups of short tracheids were often found throughout the cross-section of the tree, particularly in the spring wood which usually contained the longest ones. Where the short tracheids occurred, there was frequently a difference of as much as 100 per cent in their lengths. Therefore, the average length of the summer wood tracheids was usually greater than that of the spring wood. Crooked tracheids and areas of compression wood usually had a greater variation in length than material containing straight tracheids with concentric laminae.

In trees 1, 2, and 7 *(Pinus Taeda)*, which were of about the same age and growth rate, the tracheid length was approximately the same for a given position. The average length of the tracheids for the various levels represented by the specimens is given in tables VII and VIII. The slight differences found on the opposite sides of the tree were insignificant. In tree 5 *(Pinus Taeda)* the somewhat narrower rings were correlated with a more rapid increase in length of tracheids from pith to periphery, especially in bolts *i* and *q*. In this tree the average length was 5 mm. or more in the outer specimens except in bolt *b* which was from the butt log.

Tree 3 *(Pinus echinata)* had approximately the same length tracheids for a given growth ring as trees of *Pinus Taeda,* but the rings were much narrower; therefore, the average length in the first test specimens near the pith was approximately 4 mm. It is evident that these test specimens contained a large percentage of tracheids which were 4.5 mm. or more in length, since those of the first rings were very short.

Trees 4 and 6 *(Pinus palustris)* had somewhat shorter tracheids for a given ring than the *Pinus Taeda* trees studied, but the average length for a given specimen was greater due to the very slow growth.

The mean diameter of the tracheids increased with the increase in length. The diameter of the spring-wood tracheids was from one-third to one-half greater than those of the summer wood. The maximum diameters observed for the spring wood tracheids of *Pinus Taeda* were about 0.06 mm. in the first 2 or 3 rings to about 0.085 mm. in the outer part of the trees. For corresponding positions in the tree, *Pinus echinata* showed an increase from about 0.06 to 0.072 mm., and *Pinus palustris* from 0.05 to 0.07 mm. In the summer wood of *Pinus Taeda* the maximum diameters increased from about 0.04 mm. in the first rings to about 0.052 mm. in the outer part of the trees, in *Pinus echinata* from about 0.04 to 0.049 mm., and in *Pinus palustris* from about 0.032 to 0.044 mm. The average diameter was somewhat lower in all cases and increased in about the same ratio, but since the tracheids tapered from near the middle towards either end, it was very difficult to determine the average diameters. To give a true value it would be necessary to isolate the cells and measure them at a given point but the large numbers necessary for a significant figure made this impractical. A cursory study showed that the average diameter of the tracheids increased from the base of the tree towards the top, at least for the first few feet. Since the wood rays and resin ducts vary within small limits, the thickness of the cell walls was best reflected in the specific gravity. Therefore, it was considered unnecessary to make a statistical study of them.

TRACHEID IRREGULARITIES

The length of the tracheids, as stated above, had a definite relation to their age and position in the tree, while the differences in general contour of the cells and the thickness of the cell walls were more or less correlated with the spring and summer wood. On the other hand, the tracheids varied greatly in degree of straightness with little relation to position in the tree. In general, they were straighter in the upper and outer portions, but this relation did not hold for all trees or for all positions in a given tree. Areas of crooked tracheids occurred in any portion of the tree, and were common in the butt bolts and the first rings around the pith. Crooked tracheids occurred characteristically in compression wood but also around knots, adventitious buds, leaf traces, injuries, and in the otherwise clear wood.

Crooked tracheids can usually be detected by the irregularity of the rupture when small slivers are split from the specimen, by a rough or splintery surface in dressed material (especially in material of high density), and by a waviness in the annual rings or a curly grain. Crooked tracheids must not be confused with spiral-grain, which also may give a rough surface in dressed material, although they were found to be associated with it in tree 5. Cross- or spiral-grained material gives a rough surface if dressed against the grain and a smooth surface if dressed with it, whereas material containing unusually crooked tracheids gives an uneven surface when dressed in either direction.

Straight uniform tracheids, except for slight curvatures at the wood rays (pl. 10, fig. 3), with tapering sharp-pointed ends were found in all the trees studied, but they were accompanied by areas of crooked tracheids. Trees 1, 2, and 7 contained a large percentage of tracheids which were straight except for recurved or crooked ends. This was especially true of the very rapid-growth material near the pith and the slow-growth material in the sapwood of the older trees. In tree 5 and in certain areas of all the trees, the tracheids were wavy throughout (pl. 10, fig. 4). The V-shaped markings shown in pl. 9, fig. 3 (5bN12) were made up of these crooked tracheids. In general, where this irregularity was not due to a knot or other disturbance as stated above, the curve of one tier was opposite that of the adjacent tier so that the tracheids crossed each other (pl. 10, fig. 5). The intercellular spaces caused by the crossing of the cells prevented compactness of form and interrupted the gluing layer.

Other elements that might be classed as inferior in strength properties are compression wood, and the occurrence of parenchyma cells around the resin ducts (pl. 10, fig. 6) and in limited areas which appeared to be callus tissue. Compression wood will be discussed in detail in the next section.

THE STRUCTURE OF THE CELL WALL

The physical properties and chemical constituents of the cell walls of plants in relation to microscopic structure have attracted the attention of botanists for many years. Nägeli ('64) observed a definite concentric lamination of broad light bands alternating with narrow dark ones in the cell walls of flax fibers. He advanced the theory of alternate layers of cell wall material each containing different amounts of water. By the use of swelling reagents he observed striations on the surfaces of the fibers which he designated as fibrils. He noted further that the fibrils in adjacent laminae ran in opposite directions, each lying in a spiral around the cell. Anderson ('27) expressed the belief that the laminae were not alternate layers of water-rich and water-poor cellulose, but that they represented the boundary lines of the layers of cellulose. He later ('28a) modified his conclusions, stating that the alternate layers were of different chemical constituents, and ('28b) he observed that in the epidermis of *Clivia nobilis* the cell wall was made up of alternating layers of cellulose and pectin. Anderson ('27) and Ritter ('28) were able to separate the laminae from each other.

The middle lamella of lignified tissues was believed to be composed largely of lignin by Ritter ('25), Harlow ('27), Candlin and Schryver ('28), Harlow and Wise ('28), and Scarth, Gibbs, and Spier ('30), none of whom denied the possibility of pectin being present. The recent work of Kerr and Bailey ('33) states that the middle lamella is a combination of lignin and pectin. The secondary thickening may be composed either of cellulose and lignin (Scarth, Gibbs, and Spier, '30) or of cellulose alone. It is likely, however, that the secondary wall contains a certain amount of pectin. This is indicated by the recent work of Farr and Eckerson ('33) on the cotton fiber and of Kerr and Bailey ('33) on woody cells.

The amplification of the micellar theory of Nägeli by the use of X-rays as reviewed by Clark ('30) and Thiessen ('32) has demonstrated the dimensions and orientation of the micells, which have been found to lie at various angles to the axes of the fibers. Cotton fibers which have the greatest tensile strength are those with the fibrils parallel with the axes (Farr and Clark, '32).

Spierer constructed a special lens used as an oil-immersion objective (Seifriz, '31). Seifriz ('31) and Thiessen ('32), using the Spierer lens, reported diffraction patterns of macromicells (aggregates of true micells similar in shape to the latter) in plant cell walls. Thiessen reported the same phenomenon in partially decayed wood and coal.

The writer has been unable to substantiate this interpretation by the use of the Spierer lens at magnifications up to 2700 diameters,[4] but the laminae have been clearly outlined, thus showing in detail the gross structure of the cell wall. The cross-sections[5] of ordinary cells showed the laminae to be in the form of concentric rings or cylinders (pl. 11, fig. 1). It will be observed that the middle lamella was not differentiated from the secondary thickening. The same structure was readily demonstrated with direct illumination (pl. 11, fig. 2). Longitudinal sections of similar cells showed the laminae to be arranged uniformly and parallel with each other (pl. 11, fig. 3). The lumina of the cells appeared as dark bands, and in no instance was there any trace of macro-micells in the diffraction patterns.

"Compression wood," so-called because it was thought to be confined to the under side of limbs and leaning stems of Gymnosperms (originally described as *Rothholz* by German investigators because of its reddish color), has been described as tracheids that have rounded corners and that are characterized by a thick, heavily lignified, and spirally striated inner layer of the secondary wall.

There have been a number of theories advanced to explain the development of this type of wood, which have been reviewed by Kienholz ('30). The fact that these cells were found in abundance on the compression side of the tree led investigators to believe that they were caused by the compression stresses existing on the cells during growth, but recent findings indicate that they may be caused by gravity or by injury to the growing cells.

Both the spring and summer wood of a growth ring, or only a portion of either, may be made up of compression wood. Thin layers of it occurred in the summer-wood portion of nar-

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[4] In addition to the Spierer lens, which is an oil-immersion objective (90 x), a 30 x ocular was used.

[5] The sections were made both with and without desilicification by the use of hydrofluoric acid. The same structure was revealed in either case. This was also true of the sections of compression wood.

row rings, and isolated cells were found in both the spring and summer wood, thus completely hidden from the unaided eye (pl. 11, fig. 4). It could be readily recognized in stained sections under the microscope, however, by the difference in color caused by differential staining, the contour of the cells, and particularly by the structure of the secondary thickening of the cell walls. The white spots to be seen in the photograph cited above were due to checks which were clearly visible in the longitudinal section (pl. 11, fig. 5) and in the cross-section at higher magnification (pl. 11, fig. 6). It will also be observed that the checks lie at an angle to the longitudinal axes of the tracheids, forming a spiral around the cells (pl. 11, fig. 5).

In general, the line of demarcation between the two types of cells was very sharp where the compression wood was first laid down, but it blended gradually into the normal cells as it disappeared. All gradations of the two types of cells were found in the outer limits of the layer. The compression wood cells often had greater radial diameters and larger lumina than the adjacent summer-wood cells on either side (pl. 11, fig. 4), but this was not always the case since compression wood cells were often similar in shape and size to the ordinary cells, differing only in the structure of the secondary thickening (pl. 12, fig. 3). More highly developed compression wood cells, however, were rounded, leaving interstitial spaces (pl. 11, fig. 6).

When cross-sections of these cells were observed under high magnification (pl. 12, fig. 1), it was found that instead of concentric rings (lamellae) there were radial bands running from the region of the middle lamella to the lumen of the cell as described by Hartig ('96). These bands showed even more clearly under the Spierer lens (pl. 12, figs. 2 and 3) and their outlines and direction may also be observed with the cardeoid dark-field condenser (pl. 12, figs. 4 and 5). Although usually radial they were occasionally at an angle to the radius and were often irregular and crooked as can be seen in the illustrations. All gradations from the concentric laminae of the middle lamella to the typically radial bands shown in pl. 12, fig. 1, were found. The region of the middle lamella had the same concentric arrangement as the cells illustrated in pl. 11, fig. 1, thus making a distinct demarcation between the middle lamella and the secondary thickening (pl. 11, fig. 6). These radial bands in the secondary wall of the compression wood cells appeared then to be the lamellae so distorted and displaced that they were no longer concentric cylinders but discontinuous radial bands. At frequent intervals they separated, forming checks or cracks in the cell wall, which usually extended only through the secondary thickening. It can readily be seen that on seasoning stresses would be set up not only between the compression wood and ordinary cells but also between the middle lamellae and secondary thickenings of the same cell.

When longitudinal sections of similar compression wood cells were observed under the Spierer lens, the alternating light and dark lines were found to be running in a spiral around the fiber, similar to the checks, except in the region of the middle lamella (pl. 12, fig. 6). The same phenomenon was observed when these cells were examined under the dark field (pl. 12, fig. 7). Here, as in pl. 11, fig. 5, the spiral lines between the checks were visible, showing the identical structure which is illustrated more clearly by the Spierer lens (pl. 12, fig. 6). These sections were cut tangentially through the secondary thickening of the cell wall, and the lines are the edges of the radial laminae. Here again the middle lamella is differentiated from the secondary thickening. In the former the laminae lie parallel to the axis of the tracheids, whereas in the latter they lie in a spiral. Then, in addition to being radial, the laminae of the compression wood cells are spiral plates which may be likened to the threads in a fine screw.

In the literature the terms "compression wood" and "*Rothholz*" are confined to the reddish cells found on the under side of leaning trees and the lower side of branches, characterized by their high density and by interstitial spaces. Koehler ('30) stated, however, that "In loblolly pine and redwood relatively high longitudinal shrinkage has been found in second-growth trees with very wide annual rings containing summer wood which is not so dark and hard as in normal wood.

Such wood resembles 'compression wood' in some respects but differs from it in extending entirely around the tree trunk and in some microscopic features.'' The microscopic features were not described by Koehler.

In the present study this type of wood was abundant in the more rapid-growth *Pinus Taeda* and was found in limited quantities in the other two species. It occurred on opposite sides of the same cross-section, in isolated areas, and as individual cells. On examination it was found to have the radial laminae spirally arranged in the cell wall which were characteristic of the typical compression wood or *Rothholz* cells. Therefore, it is evident that the old terms must be modified or replaced so that they will include all cells of a similar structure regardless of color or position.

Accordingly, the writer is suggesting a new term: *torquimural* (from the Latin *torqueo,* to twist or distort, and *murus,* wall). This term is based upon the structure of the cells and not upon their occurrence, which makes it applicable to any cell having this type of structure. Torquimural cells (as found in the southern yellow pines) may be defined as *tracheids with or without interstitial spaces, moderately to very dense, the secondary wall of the individual cell differentiated from the primary wall by its radial bands or laminae which lie in a spiral around the cell.* This term is not necessarily intended to replace the older terms but to describe a definite type of cell which is characteristic of compression wood or *Rothholz* but not limited to it.

In order to differentiate the torquimural tracheids from those having concentric laminae it becomes necessary to define the latter with a corresponding term based upon the structure of the cell wall. The term *concentrimural*[6] (concentric, having a common center, and the Latin *murus,* wall) is suggested. Concentrimural tracheids may be defined as *cells usually without interstitial spaces, thin- or thick-walled, the secondary thickening and the middle lamella of which are made up of layers or laminae in the form of concentric cylinders.* These

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[6] The writer wishes to acknowledge the assistance of Mr. J. A. Moore, a graduate student in plant anatomy at Washington University, in selecting these terms.

terms will be used in the ensuing discussions where the two types of cells are compared or contrasted.

THE NATURE OF THE FAILURE AND THE DISTRIBUTION OF STRENGTH IN THE TREE

COMPRESSION FAILURES

The nature of the failure of a small specimen of clear southern yellow pine wood subjected to pressure parallel to the grain depended upon (1) the density of the material, (2) the type of cells present (torquimural or concentrimural tracheids), and (3) the moisture content. In general, the plane of the major failure was in the direction of a tangent to the annual rings (pl. 13, fig. 1), although occasionally it occurred across the rings. Thil ('00) attributed the failure along the rings rather than across them to the supposition that the wood rays were arranged in spiral rows around the tree and that the plane of the spiral was weak. Fulton ('12) and Forsaith ('21) observed that the initial cause of all failure lay in the medullary rays. The displacement of fibers around the medullary rays, the reduction in diameter at this point, and the poor cohesion between the fibers and the rays caused a point of weakness. Robinson ('21) did not attribute the initial failure in spruce to the effects of the rays, but in ash and to some extent in pitch pine the rays were effective in causing failure. Jaccard ('13) denied the existence of spiral rows of rays as reported by Thil and expressed the belief that the rays were more resistant to pressure than the fibers, that the rupture came within the ray and not between it and the fibers. He did, however, recognize the curvature of the fibers around the rays, but stated that the failure was without constant relation to the rays. Bienfait ('26) suggested that the rays added strength in the radial direction and that the failure in the tangential direction was possibly due to this stiffening effect.

Tiemann ('06), from his studies of seasoned red spruce and chestnut, suggested as a general rule that "all species of wood, which when dry show the first indication of failure under compression by a crinkling of the cell walls without bending of the fibers, would be rigid, brittle, difficult to bend without breaking, and would increase rapidly in strength with dryness, whereas species which show a tendency for the fibers to buckle without the crinkling of the cell walls would exhibit the opposite qualities.''

It is evident that Tiemann's observations were limited because the two types of failure may occur within the same growth ring and perhaps in the same cell at different degrees of dryness. Spring wood of rapid-growth material (which had large lumina and very thin walls) and brash wood (with an unusually high percentage of lignin or whose internal structure was unusual, such as torquimural cells) often crinkled or folded up, whereas concentrimural cells with thick walls usually buckled, unless the moisture content was very low. The secondary thickening of the thin-walled spring wood cell often broke loose from the middle lamella and folded into the lumen of the cell (pl. 13, fig. 2).

In specimens of green southern yellow pine under compression parallel to the grain, numerous wrinkles or offsets indicating failure were observed throughout the specimen. If the compression was continued one or more definite zones of failure developed, offsetting the specimen in one direction or forming a wedge split (pl. 13, fig. 1*b*). After the failure localized, most of the deformations over the remainder of the surface disappeared. Within this zone of failure the cells buckled, separating from each other or remaining in groups. These groups usually consisted of the tiers of fibers. In separating, the cell walls ruptured at the interface of the secondary thickening and the middle lamella, leaving the latter attached to one of the cells. In adjacent tiers of cells, the middle lamella often pulled away from the cell walls of one tier and remained attached to the other (pl. 13, fig. 2). This condition would be expected if the lignin of the middle lamella was somewhat stiffer and more brash than the cellulose walls (Dadswell and Hawley, '29).

The zone of major failure (plane of buckled cells) varied in size with the material tested. In tough green wood it often extended more than an inch along the specimen, and when the loading was continued after failure a large portion of the specimen was macerated or shredded. In general the entire mass of cells buckled in one direction (pl. 13, fig. 1*c*), but when longitudinal sections of this region of failure were examined under the microscope it was found that individual cells at various points buckled away from the larger wood rays, the cells on either side buckling in opposite directions (pl. 13, figs. 3 and 4). The natural curvature in the tracheids at the point where they pass the larger wood rays, particularly the fusiform rays, and the reduction in diameter were sufficient to cause a point of weakness. The rays running in the radial direction cause a line of cells on either side of each ray to be curved in one direction. There were from 25 to 100 fusiform rays per sq. cm. and from 2000 to 3000 linear rays per sq. cm. in the pines studied here; therefore it is the opinion of the writer that the curvature of the tracheids was the controlling factor in the direction of the failure. This was further substantiated by the fact that in a number of the specimens failing *across the rings* the tracheids were found to be crooked and the greatest curvature was in the radial direction. So far as the southern pines reported here are concerned, the rays were effective in the position and direction of the initial failure. However, there was no definite arrangement of the rays observed as assumed by Thil.

When the individual buckled cells were examined by means of the Spierer lens, it was found that the inner wall (in relation to the curve) had folded or wrinkled, whereas the outer wall was drawn tight (pl. 13, fig. 5). In the torquimural cells the walls gave way entirely (pl. 13, fig. 6) or folded up by a shredding of the spiral laminae.

The "slip planes" in the individual cells observed by Robinson ('21) and Bienfait ('26) were, in the opinion of the writer, due either to the folding of the cell walls in the region of the pits as described by Tiemann ('06) or to an artifact brought about by the rupture of the laminae which exposed the amorphous lignin and pectin and caused differential staining. Similar slip planes may also be observed in torquimural cells where the laminae separate, forming checks.

Tracheids were often observed to buckle into the resin ducts and thus become more completely separated from each other. In conclusion, it may be considered that an excess of large rays and resin ducts would reduce the strength per unit weight, but this effect was often overshadowed by crooked and otherwise inferior fibers.

STRENGTH AND STRUCTURE

The strength tests reported in this paper were made in the civil engineering laboratory at Washington University, with the assistance of Mr. Charles O. Quade and Mr. Chester Abbey[7] and under the direction of Prof. A. W. Brust, assistant professor of civil engineering.

These tests consisted of static compression parallel to the grain made on specimens 1½ x 1½ x 6 inches (specimens having a nominal length 4 times the least dimension). Since the object was primarily to determine the causes of variations in strength of material having a given density and percentage of summer wood and the distribution of strength in the tree, it was more desirable to use smaller specimens than those of a size specified by the American Society for Testing Materials (pieces 2 inches square). By using the smaller specimens it was possible to divide the cross-sections of the trees more nearly into their natural zones: inner heartwood containing short tracheids and numerous small rays, intermediate and outer heartwood containing long tracheids and larger rays, and outer sapwood. This emphasized the great differences in strength caused by differences in density and fiber characteristics in these various zones.

The compression tests were made on a 3-screw Riehle 150,000-lb. universal type testing machine at a cross head speed of 0.018 in. per minute.

Tables v (green material) and vi (seasoned material) show by bolts the number of tests, the average specific gravity, percentage of summer wood, rings per inch, and compression strength of the 7 trees used in this study. The average percentage of moisture was omitted in table v because it was above

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[7] American Creosoting Co. Fellows in the department of civil engineering, Washington University.

the fiber-saturation point and had no significance, but it was included in table VI, which represents the seasoned material. The averages given represent all the tests made on the bolts used in the microscopic studies except a few individual tests from other bolts which showed unusual strength or weakness per unit weight. The corrected specific gravity[8] and measured

TABLE V

RESULTS OF COMPRESSION TESTS AVERAGED BY BOLTS AND BY TREES—GREEN. THE AVERAGE STRENGTH IS BASED ON THE AREA REPRESENTED BY THE TESTS MADE AT VARIOUS DISTANCES FROM THE PITH

Tree and bolt No.	Species	Number of tests	Original specific gravity	Corrected specific gravity	Estimated percentage of summer wood	Measured percentage of summer wood	Rings per inch	Maximum stress #/sq.in.
5–b	*Pinus Taeda*	53	0.549	0.521 (22)*	49	57	7.8	3570
5–i	(loblolly pine)	49	0.459	0.452 (30)*	29	38	9.4	3328
5–q		41	0.426	0.409 (25)*	24	28	8.8	2594
	Ave.		0.478	0.460	34	41	8.6	3164
7–a	*Pinus Taeda*	15	0.491	0.485	48	50	5.7	3540
7–g	(loblolly pine)	12	0.452	0.446	35	44	5.1	3450
7–m		11	0.436	0.428	25	36	5.8	3360
	Ave.		0.459	0.453	36	43	5.5	3360
3–a	*Pinus echinata*	15	0.602	0.588 (14)*	36	53	10	4625
3–c	(shortleaf pine)	11	0.544	0.535 (10)*	33	46	12	4477
3–e		11	0.519	0.510 (10)*	35	43	11	4110
3–h		11	0.475	0.465	29	38	13	3840
	Ave.		0.535	0.524	33	45	11.5	4263
4–a	*Pinus palustris*	22	0.565	0.509 (21)*	38	49	20	3752
4–c	(longleaf pine)	20	0.572	0.541	36	46	21	4003
4–f		15	0.555	0.509	40		20	3669
4–h		14	0.521	0.473 (13)*	29	38	21	3293
	Ave.		0.553	0.508	35		20.5	3679
6–a	*Pinus palustris*	12	0.569	0.542	44	44	24	4063
6–e	(longleaf pine)	9	0.571	0.489	39	34	22	3977
6–i		9	0.477	0.453	32	29	21	3172
	Ave.		0.539	0.494	38	36	22	3737

* The number of specimens represented in the corrected values.

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[8] The specific gravity after correcting for resin content. These corrected values were used in all interpretations in this paper.

TABLE VI

RESULTS OF COMPRESSION TESTS AVERAGED BY BOLTS AND BY TREES—SEASONED. THE AVERAGE STRENGTH IS BASED UPON THE AREA REPRESENTED BY THE TESTS MADE AT VARIOUS DISTANCES FROM THE PITH

Tree and bolt No.	Species	Number of tests	Percentage of moisture	Original specific gravity	Corrected specific gravity	Estimated percentage of summer wood	Measured percentage of summer wood	Rings per inch	Maximum stress #/sq. in.
1–a	*Pinus Taeda*	25	6.6	0.589	0.569 (17)*	57	55	7.7	10677
1–d	(loblolly pine)	22	7.0	0.500	0.499 (17)*	34	38	7.5	9191
1–h		28	7.9	0.473	0.435 (12)*	29	30	6.9	8658
	Ave.		7.1	0.521	0.501	40	41	7.4	9508
2–a	*Pinus Taeda*	28	8.0	0.596	0.576 (20)*	52	53	5.4	11692
2–d	(loblolly pine)	24	6.2	0.508	0.488 (14)*	43	41	4.5	9512
2–h		24	7.7	0.495	0.479 (22)*	30	35	4.0	8775
	Ave.		7.3	0.533	0.514	41	43	4.6	9993

* The number of specimens represented in the corrected values.

summer wood[9] are given where a sufficient number of tests was made to justify a comparison. Where there were fewer tests the number is given in parentheses followed by an asterisk. The estimated summer wood was on the whole lower than the measured values.

These averages show particularly the variations in density and strength at the different heights in the tree. They also show to a certain degree the differences in strength shown by the various species. In the green condition *Pinus echinata* was consistently stronger than *Pinus palustris* which in turn was stronger than *Pinus Taeda* except for one bolt in tree 4 (fig. 3). The strength decreased from the base towards the top of the tree. The strongest material was in the lower bolts except in tree 4 where the strength reached a maximum in bolt *c* about 12 feet from the ground. In the lower part of the tree the strength fluctuated from bolt to bolt, but the maximum was invariably in the lower 12 to 15 feet in all three species. However, the maximum strength per unit weight was often

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[9] The summer wood as measured under the microscope. Only the measured summer wood is given in the other tables and the text.

between the 20- to 40-foot level in the trees. The seasoned material of trees 1 and 2 showed the same relationship (fig. 3).

Tables VII (green material) and VIII (seasoned material) show results of individual tests and microscopic studies taken within each bolt. They show particularly the variations in properties which occur from the pith to the bark and to a certain extent on the opposite sides of a cross-section. In order to obtain a sample of the average material for microscopic study at least one series of specimens from the pith to the bark on the north side of each bolt was used. The north side was arbitrarily chosen since no one side was consistently weak or strong. In addition, the percentage of resin was determined for a large number of specimens on the other three sides of each bolt, and the specific gravity (corrected for resin content)

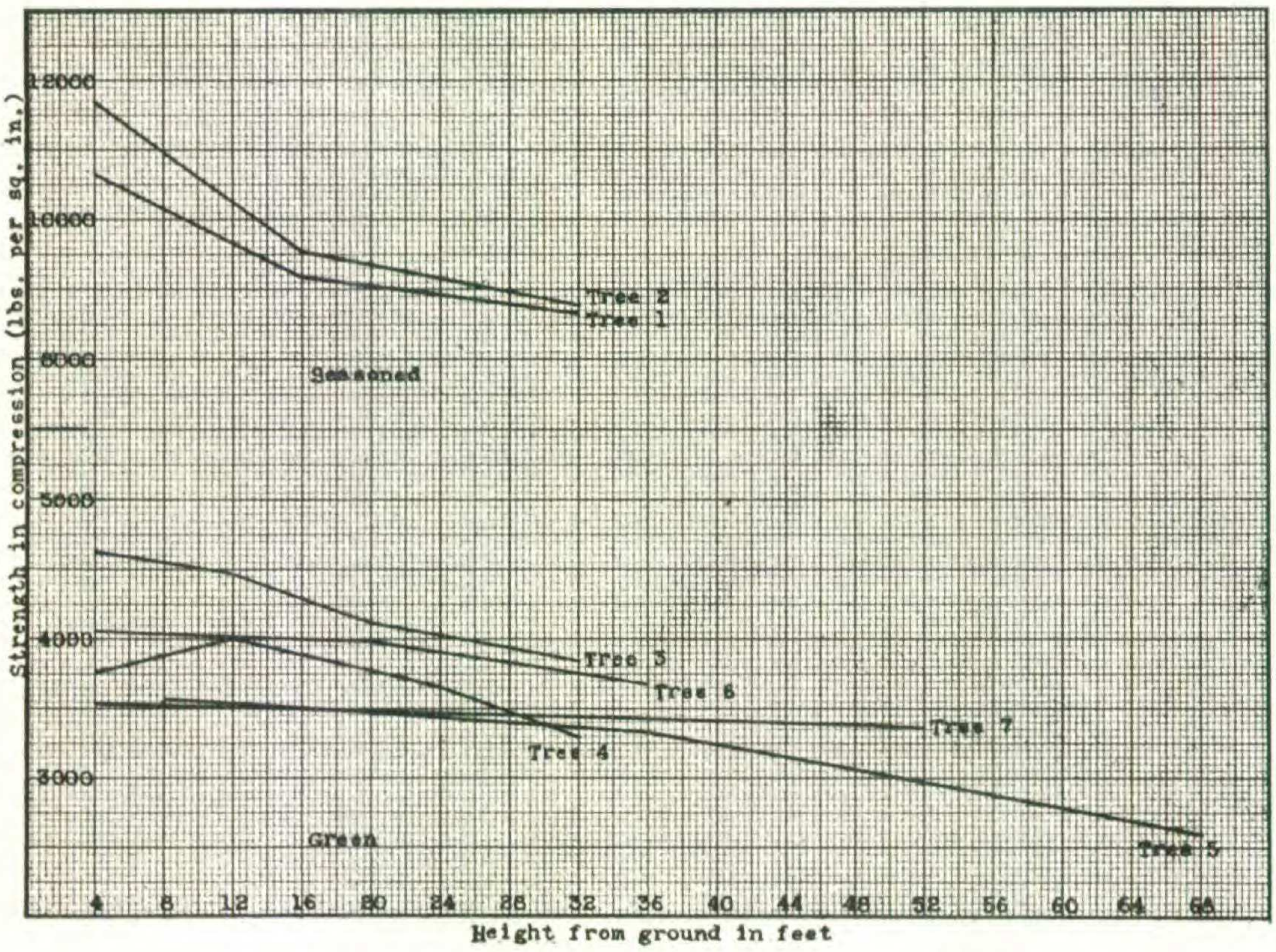

Fig. 3. The variation of strength with height in tree: below, the five trees tested green (trees 5 and 7, *Pinus Taeda*, loblolly pine, tree 3, *Pinus echinata*, shortleaf pine, and trees 4 and 6, *Pinus palustris*, longleaf pine); above, trees 1 and 2 (*Pinus Taeda*, loblolly pine) tested in the seasoned condition. The average strength of each bolt was obtained by evaluating the tests by the area represented in the cross-sections (tables V and VI).

plotted against the strength. The specimens showing unusual strength or weakness were then studied microscopically. By this method material having average or very high strength and very low strength for its specific gravity was included. More material would necessarily have included a greater number of variations but the maximum range for the material represented was covered.

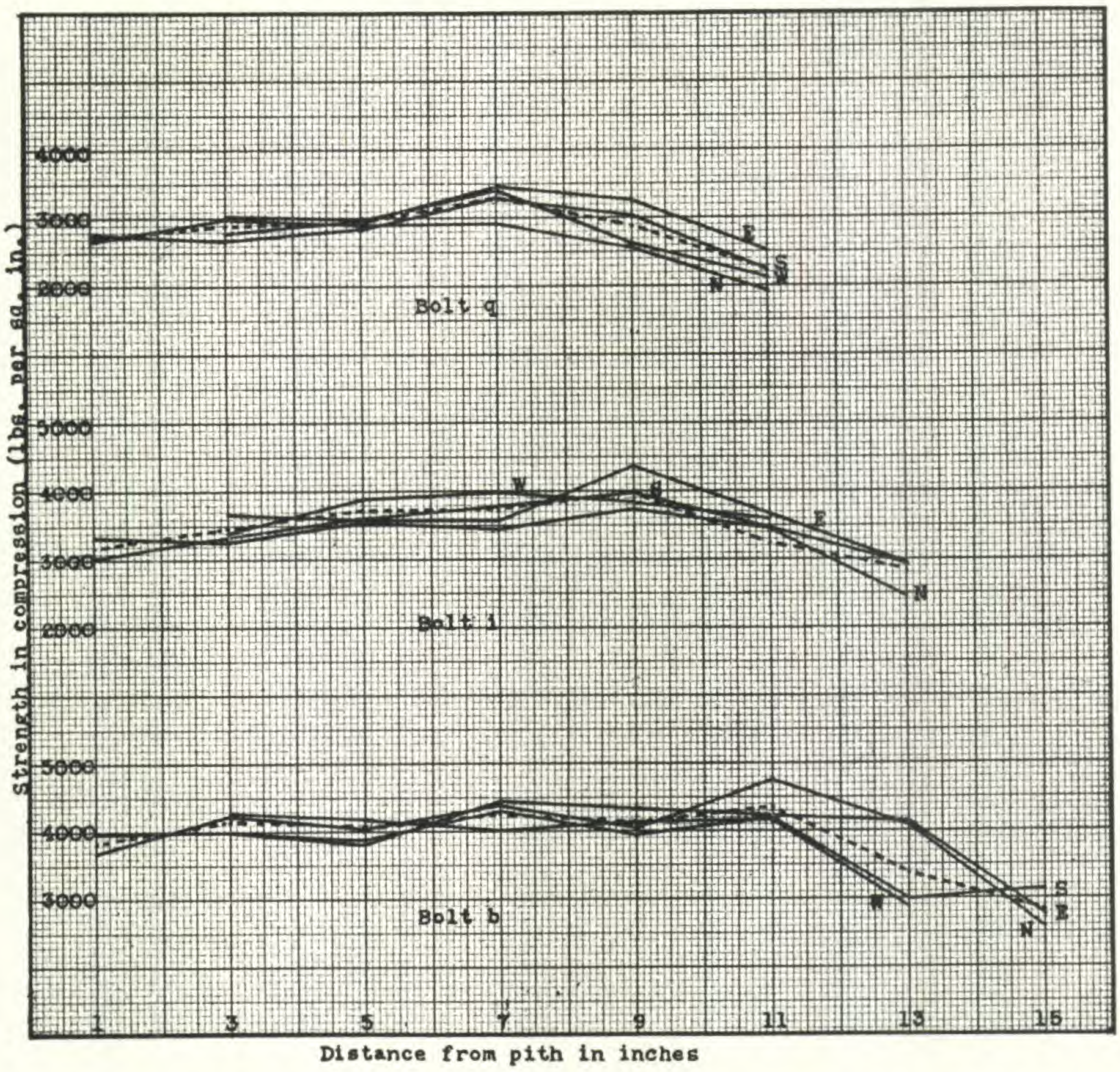

Fig. 4. Tree 5 (*Pinus Taeda*, loblolly pine), green. The solid lines represent the compression strength plotted against the distance from the pith for a single series of tests; the broken lines, the averages of all tests. Note how closely the average of all tests represents those plotted.

In the cross-section of tree 5 *(Pinus Taeda)* the strength increased from the region of the first annual rings towards the bark. It reached a maximum at about 11, 9, and 7 inches from the pith in bolts *b, i,* and *q,* respectively, after which it decreased to a minimum in the outer sapwood (fig. 4). The tra-

TABLE VII

RESULTS OF MICROSCOPIC STUDIES AND RESIN DETERMINATIONS, TOGETHER WITH THE COMPRESSION STRENGTH, OF THE INDIVIDUAL SPECIMENS OF FIVE TREES—GREEN

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings / in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 5—*Pinus Taeda* (loblolly pine)									
5bN1	3680	0.494	2.7	34	44	10	3.0	6.90	1.53
5bN3	4240	0.547	2.4	32	53	6	3.5		1.13
5bN5	4020	0.577	2.5	36	62	5	3.7		1.13
5bN7	4380	0.595	1.9	33	63	5	4.0	8.51	1.74
5bN9	4040	0.574	2.0	35	60	4	4.3		1.83
5bN11	4750	0.588	2.1		65	8	4.5		1.37
5bN12–1	4640	0.544	2.3	35	60	7			1.37
5bN13	4090	0.546	2.4	39	60	9	4.6		1.23
5bN15	2570	0.428	2.6	104	53	23	4.6	9.72	1.27
5bN16–1	2520	0.450	2.5	125	50	14			1.59
5bS1	3970	0.480	1.8	36	54	9			1.71
5bS5	3880	0.572	1.9	32	63	5			1.22
5bS10–1	4450	0.559	1.7	34		8			
5bS13	2990	0.481	1.3	85		9			
5bS16–1	3230	0.407	2.5	111		19			
5bE3	3990	0.571	8.0	29	52	6			1.20
5bE5	3840	0.584	1.7	35	57	5		8.20	1.06
5bS3–6	3110	0.488	1.0	52		11			
5bE15	2750	0.460	2.0	106	48	14			1.49
5bN3–3	4030	0.588	1.9	34	56	5		9.75	0.88
5bW1–3	2870	0.464	2.6	99		15			
5bN3–6	3050	0.483	2.4	89	51	13			1.48

5iN1	3330	0.420	1.2	31	19	6	2.6	6.34	1.31
5iN3	3250	0.440	1.8	32	31	5	4.0		1.14
5iN4–1	3610	0.462	0.4	33	38	5			1.24
5iN5	3520	0.466	1.7	30	42	6	4.3		1.17
5iN6–1	3760	0.451	1.6	33	40	6			1.25
5iN7	3440	0.458	1.6	33	42	6	4.5	7.76	1.19
5iN8–1	3450	0.442	0.7	34	43	6			1.29
5iN9	3720	0.469	1.0	34	41	7	4.8		1.22
5iN10–1	3930	0.451	1.0	34	43	8		7.96	1.16
5iN11	3450	0.485	1.3	97	44	9	5.1		0.92
5iN13	2450	0.404	1.5	144	34	25	5.2	7.74	1.67
5iS1	3000	0.403	3.2	29		5			
5iS3	3280	0.443	1.3	34		5			
5iS5	3590	0.460	1.1	34	32	6			1.06
5iS7	3780	0.464	1.0	34	40	6			1.12
5iS8–1	3990	0.496	1.1	32	41	7			1.49
5iS9	3960	0.489	1.0	34		8			
5iS10–1	4130	0.492	2.0	34	39	9			1.63
5iS11	3470	0.446	1.4	42		11			
5iS13	2910	0.429	2.2	145		21			
5iE3	3660	0.445	1.7	33	35	6			1.14
5iS3–1	3590	0.455	1.9	33	33	6			1.29
5iS3–3	3940	0.494	1.6	33	42	7			1.26
5iE9	4390	0.486	1.5	31	45	7			1.26
5iW3	3380	0.422	1.0	33	33	6			1.13
5iW5	3870	0.456	1.0	33	40	6			1.17
5iN3–2	3940	0.467	1.7	33	42	6			1.22
5iW7	3950	0.477	1.6	35	42	7			1.32
5iN3–3	3850	0.448	4.0	32	42	7		7.89	1.31
5iN3–4	3840	0.445	1.8	35	38	10			1.52

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VII (Continued)

Specimen	Maximum stress ♯/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
5qN1	2665	0.378	5.4	30	17	4	2.5	6.18	1.19
5qN3	2980	0.403	2.3	32	30	5	3.8		1.18
5qN5	2900	0.399	4.7	33	29	5	4.3	10.60	1.12
5qN7	2920	0.422	2.4	30	33	7	4.6		1.42
5qN9	2560	0.419	2.0	45	32	11	4.7		1.25
5qN11	1925	0.362	3.8	162	28	22	5.1	8.06	1.65
5qS1	2760	0.396	4.3	33		4			
5qS3	2660	0.390	2.3	32		5			
5qS5	2810	0.405	2.0	32		6			
5qS7	3295	0.445	1.4	32	33	7			1.46
5qS8–1	3390	0.436	1.0	33	38	9			1.08
5qS9	3030	0.432	2.7	72		9			
5qS11	2210	0.382	4.2	153		15			
5qS12–1	2135	0.375	3.5	182	28	12			1.38
5qE3	2785	0.416	2.6	35		6			
5qE5	2940	0.420	2.9	34		5			
5qE7	3460	0.429	2.7	32	35	8			1.18
5qE9	3245	0.436	2.5	34		9			
5qE11	2500	0.415	3.5	136	30	13			1.56
5qS3–5	2605	0.443	2.0	147	39	16			1.34
5qW3	3015	0.410	4.5	30		6			
5qW5	2965	0.406	2.4	32		6			
5qW7	3410	0.470	2.9	33		9			
5qW9	2625	0.412	4.0	117		12			
5qW11	2115	0.336	3.1	178		22			

Tree 7—*Pinus Taeda* (loblolly pine)

7aN1	2805	0.437	1.4	39	34	5	3.0	7.98	1.12
7aN3	3245	0.449	1.9	39	40	4	3.9	9.06	1.20
7aN5	3390	0.468	1.0	128	40	6	4.5	8.94	1.29
7aN7	3695	0.500	1.1	107	49	7	4.8	7.81	1.25
7aS1	3565	0.497	1.7	36	52	5			1.03
7aS3	3450	0.504	0.8	109	50	6			1.03
7aS5	3480	0.	1.0		53	4			1.33
7aS7	3865	0.527	0.8	84	65	8			1.88
7aE3	3110	0.448	2.9	44	46	4			1.34
7aE5	3025	0.439	1.2	127	51	6			1.29
7aE7	3090	0.459	1.5	119	58	4			1.87
7aE9	3530	0.478	0.7	114	47	8			1.49
7aW3	3705	0.535	0.8	103	55	6			1.15
7aW5	3955	0.536	0.7	102	47	7			1.27
7aW7	3975	0.513	0.9	106	58	11			1.53
7gN1	3245	0.430	1.1	34	33	4	3.2	7.09	1.03
7gN3	3065	0.410	1.3	49	36	5	4.1	7.08	1.07
7gN5	3115	0.406	0.7	140	40	7	4.9	7.13	1.12
7gS1	2765	0.431	1.5	33	35	4			0.94
7gS3	3025	0.434	0.7	114	44	5			0.90
7gS5	3510	0.470	1.8	109	53	6			1.18
7gS7	3705	0.491	0.8	105	58	7		6.34	1.31
7gE3	2960	0.422	4.0	33	48	3			0.90
7gE5	2810	0.420	1.0	120	41	5			1.10
7gE7	3580	0.476	0.8	123	45	5			1.00

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VII (Continued)

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 7 (Continued)									
7gW3	3580	0.483	1.3	106	46	5			0.95
7gW5	3725	0.482	1.3	120	50	7			1.33
7mN1	2915	0.399	1.4	45	28	4	3.0	7.50	0.92
7mN3	3050	0.426	1.0	147	36	9	4.1	7.60	1.18
7mN5	3420	0.455	1.2	134	44	10	4.8	7.43	1.37
7mS1	2955	0.399	1.5	34	18	4			1.03
7mS3	2945	0.418	8.2	33	34	3			1.07
7mS5	2835	0.415	1.0	126	32	4			1.03
7mS7	2990	0.437	1.0	137	44	7		8.04	1.29
7mE3	2890	0.427	1.0	136	36	5			1.05
7mE5	3490	0.465	1.0	130	48	10			1.64
7mW3	3185	0.421	0.7	77	37	4			1.03
7mW5	3335	0.451	0.8	124	42	6			1.15
Tree 3—*Pinus echinata* (shortleaf pine)									
3aN2	5850	0.614	2.6	29	58	13	4.0	5.87	1.24
3aN4	5720	0.612	3.3	29	58	8	4.2	6.26	0.72
3aN6	4240	0.580	3.6	74	63	6	4.6	6.04	0.73
3aN8	4260	0.543	3.3	83	52	10	4.9	6.37	0.71
3aN10	4150	0.542	1.4	93	51	14	4.9	6.50	0.97

3aS2	4760	0.528	3.0	32	44	11	3.1		0.80
3aS4	4400	0.549	3.3	54	45	9	4.2		0.92
3aS6	4140	0.536	2.4	97	46	14	4.7		1.04
3aE3	5900	0.684	1.3	30	59	14	4.1		0.84
3aE5	5370	0.685	3.5	33	57	15			0.94
3aE7	4950	0.700	2.1	30	61	9	4.3		0.94
3aE9	4760	0.598	3.0	32	57	13			1.08
3aW3	3920	0.526	1.9	103	45	15	3.8		0.92
3aW5	4240	0.537	2.8	84	49	15	4.2		1.01
3cN4	4960	0.557	2.6	33	47	11	4.7	5.82	0.71
3cN6	4780	0.566	2.4	34	48	8	4.9	6.33	0.92
3cN8	4280	0.555	0.9	96	46	9	5.0	6.23	0.69
3cN10	4380	0.531	0.9	109	45	10	5.1	6.30	0.70
3cS2	4260	0.493	3.0	30	44	18			1.07
3cS4	4150	0.506	1.5	91	48	13	5.0		1.07
3cS6	4120	0.527	1.7	107	48	18			
3cE3	5090	0.570	1.6	113	50	12			
3cE5	4600	0.557	1.6	111	50	10	5.1		
3cW3	3930	0.487	1.5	34	46	12			
3eN2	4220	0.506	3.0	40	50	15	3.8	5.94	0.83
3eN4	4660	0.529	2.9	45	48	9	4.7	5.83	0.80
3eN6	4210	0.518	2.6	82	40	11	4.9	6.27	0.89
3eN8	3950	0.508	2.5	95	44	10	5.0	6.85	0.78

* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VII (Continued)

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 3 (Continued)									
3eS4	4080	0.509	1.0	107	45	10			0.71
3eS6	4000	0.527	1.1	94	44	15			0.73
3eE3	3980	0.533	1.2	93	40	15			
3eE5	4180	0.537	0.9	100	48	10			
3eW3	3230	0.458	2.3	33	40	9			0.70
3eS4–1	3520	0.474	2.1	60	35	10			
3hN2	3830	0.447	3.9	29	23	11	3.8	6.08	0.89
3hN4	4070	0.500	1.5	88	40	10	4.8	5.96	0.75
3hN6	3780	0.486	1.6	108	39	10	5.0	5.82	0.60
3hS2	3290	0.402	3.9	32	14	11			0.78
3hS4	3680	0.451	3.7	47	44	12			0.83
3hS6	3840	0.473	2.4	109	39	21			0.74
3hE3	4110	0.470	1.0	31	41	12			
3hE5	4210	0.508	1.6	97	47	17			
3hE7	3970	0.501	1.0	100	43	14			
3hW3	3230	0.434	1.6	43	40	10			0.59
3hW5	3110	0.448	1.5	127	35	9			

Tree 4—*Pinus palustris* (longleaf pine)

4aN1	4020	0.530	2.9	35		40			
4aN2	5330	0.607	6.7	29	46	33	4.4	6.46	1.07
4aN3	5230	0.593	8.0	29		20			
4aN4	5780	0.654	5.1	32	60	15	4.8	7.00	1.10
4aN5	4260	0.524	7.8	54		15			
4aN6	4900	0.577	12.0	34	45	16	5.0	7.17	1.21
4aN7	3420	0.531	1.9	110		18			
4aN8	3520	0.500	3.2	116	45	20	5.1	7.95	1.34
4aS1	4310	0.554	12.3	26	35	27			1.00
4aS2	4100	0.502	11.2	32		29	4.2		
4aS3	3020	0.508	2.3	124		19			
4aS4	3000	0.486	2.3	128		20	4.7		
4aS5	2740	0.499	2.4	114	45	15			1.57
4aS6	2830	0.468	4.6	120		11	4.8		
4aE3	4840	0.623	9.3	26	49	17	4.5		1.13
4aE4	2960	0.457	4.1	126		24			
4aE5	3560	0.490	3.0	118		20	5.0		
4aW3	3830	0.508	6.9	86		22	4.8		
4aW4	4260	0.543	9.3	39		19			
4aW5	3460	0.509	1.9	113		18			
4aW6	3600	0.554	1.1	99		14			
4cN1	4570	0.538	4.9	28	39	36			1.08
4cN2	4670	0.652	4.5	22	40	33	4.0	7.59	1.22
4cN3	4420	0.557	6.8	33	52	24			1.27
4cN4	4970	0.581	7.1	29	53	20	4.9	7.20	1.27
4cN5	3690	0.508	3.1	107	57	21			1.17
4cN6	3440	0.531	3.4	108	35	27	5.2	7.63	1.26

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VII (Continued)

Specimen	Maximum stress ♯/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings / in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 4 (Continued)									
4cS1	4440	0.564	3.9	29		28			
4cS2	4220	0.541	9.5	27		23	4.6		
4cS3	3920	0.503	10.6	69		19			
4cS4	3840	0.567	4.2	85		18	4.8		
4cS5	3990	0.502	2.2	104	51	13			0.89
4cS6	4000	0.525	1.3	103		12	5.1		
4cE3	5230	0.620	2.5	29		16	4.7		
4cE4	4440	0.545	10.4	25		15			
4cE5	3810	0.518	6.6	102		28	5.2		
4cE6	3440	0.491	5.3	116		20			
4cW3	4040	0.525	6.1	79		23	4.8		
4cW4	3720	0.475	6.3	86		25			
4cW5	4060	0.545	4.9	96		16	5.0		
4cW6	4040	0.536	5.2	97		14			
4fN1	4140	0.563	22.4	23		22			
4fN2	2320	0.545	29.1	23	37	29			1.17
4fN3	3460	0.497	2.2	77		22			
4fN4	3970	0.518	4.9	54	38	21			0.92
4fN5	3860	0.539	1.2	100		13			
4fS1	4170	0.541	17.3	27	38	25			1.14
4fS2	4160	0.542	11.0	28		16			
4fS3	3080	0.446	2.4	111		26			
4fS4	3150	0.460	1.4	116		22			

4fE3	4110	0.524	1.9	57		23			
4fE4	3220	0.462	2.4	94		26			
4fE5	3330	0.483	1.5	116		23			
4fW3	3690	0.504	2.7	81		18			
4fW4	3560	0.483	3.3	66		19			
4fW6	3820	0.538	0.9	97		14			
4hN1	3150	0.528	23.5	23	41	22		5.80	1.15
4hN2	3930	(0.601)		27	39	20	4.1		0.85
4hN3	2890	0.500	7.7	36	36	29		6.08	1.06
4hN4	3630	0.554	7.4	69	37	22	5.2		0.96
4hS2	3350	0.470	10.9	32		18	4.3		
4hS3	2960	0.448	4.8	125		21			
4hS4	3040	0.436	1.2	137	38	24	5.1		1.15
4hE3	3450	0.471	5.7	79		17			
4hE4	3030	0.418	4.1	127		23	5.0		
4hW3	3270	0.457	4.6	118		22	5.0		
4hW4	3180	0.438	8.1	83		28			
4hW5	3350	0.478	5.3	115		20			
4hW6	3300	0.471	3.5	65		16			

* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VII (Continued)

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 6—*Pinus palustris* (longleaf pine)									
6aN1	6300	0.620	8.6	25	47	42	4.4	6.14	1.45
6aN3	4250	0.479	4.1	91	45	12	4.7	6.34	0.90
6aN5	3570	0.507	3.0	107	39	17	4.8	8.26	1.82
6aS1	5365	0.575	5.0	30	38	44			1.48
6aS3	5830	0.580	8.2	35	43	39			1.81
6aS5	4270	0.536	1.9	97	46	10			1.15
6aS7	3770	0.498	1.5	115	35	20	4.9	8.11	1.41
6aE3	4040	0.514	1.9	95	44	16			1.14
6aE5	4285	0.542	2.6	97	45	22			1.87
6aW3	5830	0.622	10.9	26	59	30			1.39
6aW5	4190	0.522	2.9	86	45	12			1.10
6aW7	3655	0.513	2.5	107	39	21			1.59
6eN1	3800	0.520	4.5	32	22	36	4.0	5.79	1.69
6eN3	4800	0.529	6.2	30	36	41	4.7	5.70	1.51
6eN5	3830	0.488	4.7	72	33	16	5.0	6.96	1.32
6eS1	4000	0.493	3.1	88	36	15			0.66
6eS3	3290	0.468	3.4	126	30	18			1.24
6eS5	3540	0.480	2.5	126	35	16			1.49
6eE3	3565	0.473	2.5	105	32	14			0.96
6eE5	4740	0.555	1.7	95	52	13			1.08

6eW3	3670	0.482	5.2	85	28	25			0.99
6iN1	4265	0.525	15.7	27	26	38	4.5	6.03	1.32
6iN3	2675	0.403	9.2	100	19	19	4.8	6.33	1.07
6iN5	2755	0.407	4.0	157	25	26	5.0	8.41	1.65
6iS1	4825	0.495	11.8		45	17			1.01
6iS3	3840	0.506	3.3	65	33	14			0.69
6iS5	2865	0.409	3.9	155	23	21			1.55
6iE3	3480	0.457	4.8	80	31	13			0.73
6iE5	3425	0.472	2.0	124	33	22			1.20
6iW3	2745	0.404	2.3	148	25	16			1.03

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

TABLE VIII

RESULTS OF MICROSCOPIC STUDIES AND RESIN DETERMINATIONS ON THE INDIVIDUAL SPECIMENS—SEASONED

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 1—*Pinus Taeda* (loblolly pine)									
1aN1	6430	0.526	5.4	6.5	35	3			
1aN2	6750	0.402	11.9	8.4	29	3	2.9	8.92	1.32
1aN3	8830	0.493	2.3	6.8	55	10			
1aN4	8770	0.526	2.4	6.8	59	10	4.0	8.82	1.61
1aN5	9870	0.566	2.0	7.1	65	6			
1aN6	9210	0.562	2.1	7.0	59	6	4.3	9.41	1.68
1aN7	9300	0.606	0.9	7.1	70	7		10.25	1.62
1aN8	8720	0.597	2.3	7.2	65	6	4.6	10.29	1.89
1aS2	8730	0.593	3.7	6.0	38	4		9.16	1.27
1aS4	12460	0.652	3.0	6.2	68	11			1.58
1aS5	14370	0.701	1.2	6.7	64	11			1.62
1aS6	13620	0.653	2.7	6.6	60	9			1.60
1aE3	10000	0.653	3.0	6.9		10			
1aE5	10840	0.554	2.4	6.8		7			
1aE7	9500	0.506	2.7	6.7		8			
1aW4	9470	0.540	3.0	6.4	55	10			1.35
1aW5	13120	0.638	2.2	6.5	60	7			1.27
1dN1	6440	0.404	2.0	6.7	11	3			
1dN2	6320	0.402	2.3	7.3	11	3	2.9	9.35	1.25
1dN4	7760	0.452	1.2	7.2	40	7	4.2	7.94	1.10
1dN6	8580	0.501	1.3	7.3	46	7	4.8	8.32	1.05

1dS2	6620	0.441	3.8	6.7	11	3			1.26
1dS3	10280	0.501	1.2	6.6	43	6			1.26
1dS4	10430	0.541	1.8	6.8	50	8			1.30
1dS5	11960	0.571	1.0	6.9	50	11			1.26
1dS6	13100	0.615	1.6	6.9	57	11			1.72
1dE3	8570	0.482	1.4	7.5		10			
1dE4	10320	0.503	1.1	7.3	43	10			1.08
1dE5	10260	0.500	1.4	7.3	48	7		8.54	1.40
1dE6	9940	0.484	1.0	7.3	47	8		8.08	1.40
1dE7	8390	0.470	1.7	8.5		9	5.0		
1dW3	10920	0.509	1.1	6.9	45	10		7.34	1.40
1dW5	11250	0.562	1.2	6.6		11			
1dW6	11380	0.562	1.1	6.4	53	9			1.50
1hN1	7240	0.430	2.4	8.0		5			
1hN2	5950	0.382	5.5	8.2	12	3	3.0	7.99	1.26
1hN4	7010	0.440	1.4	8.4	33	5	4.2	7.85	0.82
1hN6	8190	0.476	1.5	8.2	37	7	4.9	8.03	1.24
1hS1	6390	0.428	5.2	7.8	21	3			0.88
1hS2	6790	0.438	2.9	7.7	21	4			1.02
1hS4	9660	0.491	1.5	7.5	44	6			1.09
1hS6	8510	0.458	0.8	7.6	43	9			1.20
1hE3	7600	0.444	1.1	7.9		6			
1hE5	8610	0.448	2.2	7.9		9			
1hW3	6690	0.468	1.9	7.7		5			
1hW5	10100	0.510	1.3	7.9		12			

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

Table VIII (Continued)

Specimen	Maximum stress #/sq. in.	Specific gravity*	Percentage of resin	Percentage of moisture	Percentage of summer wood†	Rings/in.	Tracheid length in mm.	Percentage of area taken up by rays	Percentage of area taken up by resin ducts
Tree 2—*Pinus Taeda* (loblolly pine)									
2aN2	6500	0.455	4.1	10.3	31	3	2.8	8.75	1.86
2aN4	11330	0.610	1.6	9.9	58	6	3.7	8.66	2.08
2aN5	13940	0.641	0.5	6.8	60	7			1.65
2aN6	12130	0.591	1.1	9.9	62	7	4.4	9.98	1.32
2aN9	13340	0.619	0.6	10.1	63	7	4.9	9.42	1.47
2aS1	6760	0.412	13.0	9.7	17	3			2.38
2aS2	9000	0.555	10.0	8.7	35	4			2.25
2aS3	8160	0.527	4.7	7.0	33	3			1.73
2aS4	9870	0.566	7.8	11.1	50	3			2.03
2aS5	12060	0.578	1.0	7.0	57	5			1.52
2aS6	12400	0.620	1.4	10.4	60	5			1.75
2aS8	12820	0.617	1.3	9.5	60	6			1.60
2aE3	11800	0.595	1.6	6.0	55	5			1.54
2aE5	11330	0.621	1.7	7.2	60	5			1.44
2aE6	9940	0.573	1.6	7.1	63	5			1.22
2aE7	10560	0.623	1.9	7.2	65	5		9.84	1.88
2aE8	9650	0.578	1.2	7.6	65	6			1.90
2aW3	11600	0.552	1.7	7.2	50	5			1.54
2aW5	13000	0.628	2.2	7.0	65	6			1.65
2aW7	13000	0.623	1.9	7.0	62	10			1.83
2dN1	6100	0.434	21.2	8.3	17	2			2.05
2dN2	7170	0.427	3.7	6.6	30	2	3.0	8.02	1.51
2dN4	7800	0.466	0.9	6.1	48	3	3.7	7.81	1.58
2dN5	8010	0.524	1.8	6.2	45	5			1.61
2dN6	8650	0.516	1.1	6.5	50	4	4.5	8.65	1.40
2dN8	8430	0.500	0.7	6.4	50	5	5.0	9.59	1.47

2dS2	6700	0.446	15.4	6.7	15	3			3.15
2dS4	10830	0.519	0.5	6.2	52	5			1.92
2dS6	12150	0.552	0.9	6.0	52	6		9.15	2.02
2dE3	8370	0.486	0.5	5.8		4			
2dE5	8980	0.533	0.8	5.9		4			
2dE7	9260	0.526	0.5	5.9		7			
2dW3	9960	0.514	1.2	5.5		4			
2dW5	12270	0.502	1.4	7.0	54	6			1.61
2hN1	6240	0.376	20.8	8.7	20	3			2.50
2hN2	7000	0.452	6.8	7.7	20	2	3.1	8.36	1.34
2hN3	8140	0.422	3.9	8.0	26	2		7.88	1.85
2hN4	7910	0.433	1.8	7.7	30	3	4.0	7.88	1.85
2hN5	9260	0.472	2.3	7.7	33	3			1.95
2hN6	8360	0.454	1.0	7.5	37	3	4.5	7.85	1.71
2hN8	10720	0.511	0.9	6.6	49	8	5.1	9.75	1.70
2hS1	6820	0.456	5.5	7.4	20	2			1.66
2hS2	7520	0.455	9.0	8.1	21	3			1.82
2hS3	9750	0.495	1.0	7.8	43	4			1.49
2hS4	9550	0.506	1.0	7.3	42	5			1.46
2hS5	10440	0.524	2.0	7.3	47	5			1.41
2hS6	10400	0.522	0.9	7.3	48	6			1.59
2hE3	7220	0.444	1.2	7.7	30	2			1.54
2hE4	6520	0.455	2.6	8.1	34	3			1.60
2hE5	7450	0.510	1.1	7.7	32	3			1.71
2hE6	7780	0.524	2.3	7.7	56	3		9.61	2.20
2hE7	7680	0.504	1.4	7.7	37	6			1.49
2hE8	7250	0.501	2.2	7.8	40	7			1.64
2hW3	8270	0.477	1.4	7.8		3			
2hW4	7970	0.428	1.8	8.8	32	3			1.86
2hW6	9720	0.533	1.0	7.6		6			

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* The specific gravity as reported here was corrected for resin content.

† The percentage of summer wood was determined by measuring the rings under the microscope.

cheid length and the density increased with the strength to a maximum, after which the density decreased with the strength, but the tracheid length only fluctuated within small limits. The resin ducts and to a certain extent the area taken up by the rays increased in this weak material of the outer sapwood. There were certain fluctuations in strength on the opposite sides of the cross-section, as well as in side-matched specimens from the same side due to the presence of torquimural and crooked tracheids and an accumulative effect of minor defects and injuries caused by strain in the living tree, but any given series of specimens from the pith to the periphery, when plotted, resembled in general any other series from the same bolt or the average of all of them. In each of the three bolts (*b, i,* and *q*) there were 8 series of specimens tested from the inner portion of the tree to the periphery (see fig. 1 for the relative positions of the 8 series of specimens). Four series of tests were plotted in fig. 4, together with the average of all 8 series. The agreement was very close at all points except bolt *i*, 11 inches from the pith. In this tree the growth rate was medium to rapid for the first 7–11 inches from the center, depending upon the bolt, thus placing the region of greatest density and strength some distance from the pith. The outer portion was of very slow growth and low density and strength. Figure 5, for tree 7 *(Pinus Taeda)* shows an increase of strength from the pith to the periphery. This tree, being much younger than tree 5, did not show a decline of strength in the outer sapwood.

The average strength decreased from the inner specimens towards the periphery in bolt *a* of tree 3 *(Pinus echinata)* and remained practically constant in bolts *c* and *e,* with a slight increase in the same direction in bolt *h* (fig. 6). The growth rate was very slow in the first 2–4 inches in bolt *a,* after which it increased at a moderate rate, but at the higher levels the growth rate was more rapid in the inner heartwood and the region of greatest strength was therefore farther from the pith.

The wide fluctuations in strength at a given distance from the pith in this and the two following trees were due to the asymmetric growth and crookedness of the trees, which made it impossible to obtain side-matched specimens from the same

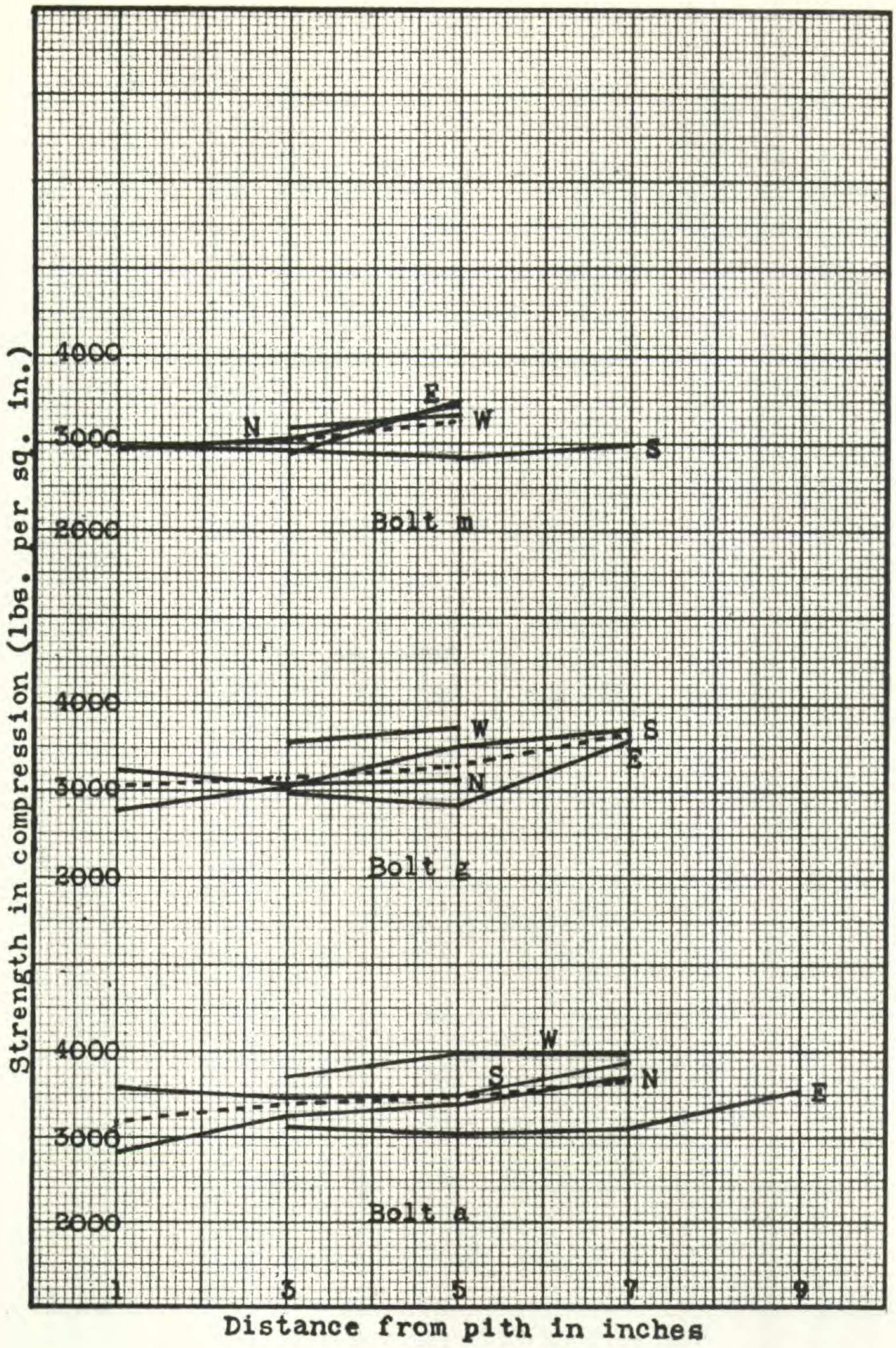

Fig. 5. Tree 7 (*Pinus Taeda*, loblolly pine), green. The solid lines represent the compression strength plotted against the distance from the pith for a single series of tests. The broken lines, the averages of these tests. Note that the average strength increased from the pith towards the periphery of the stem in all three bolts.

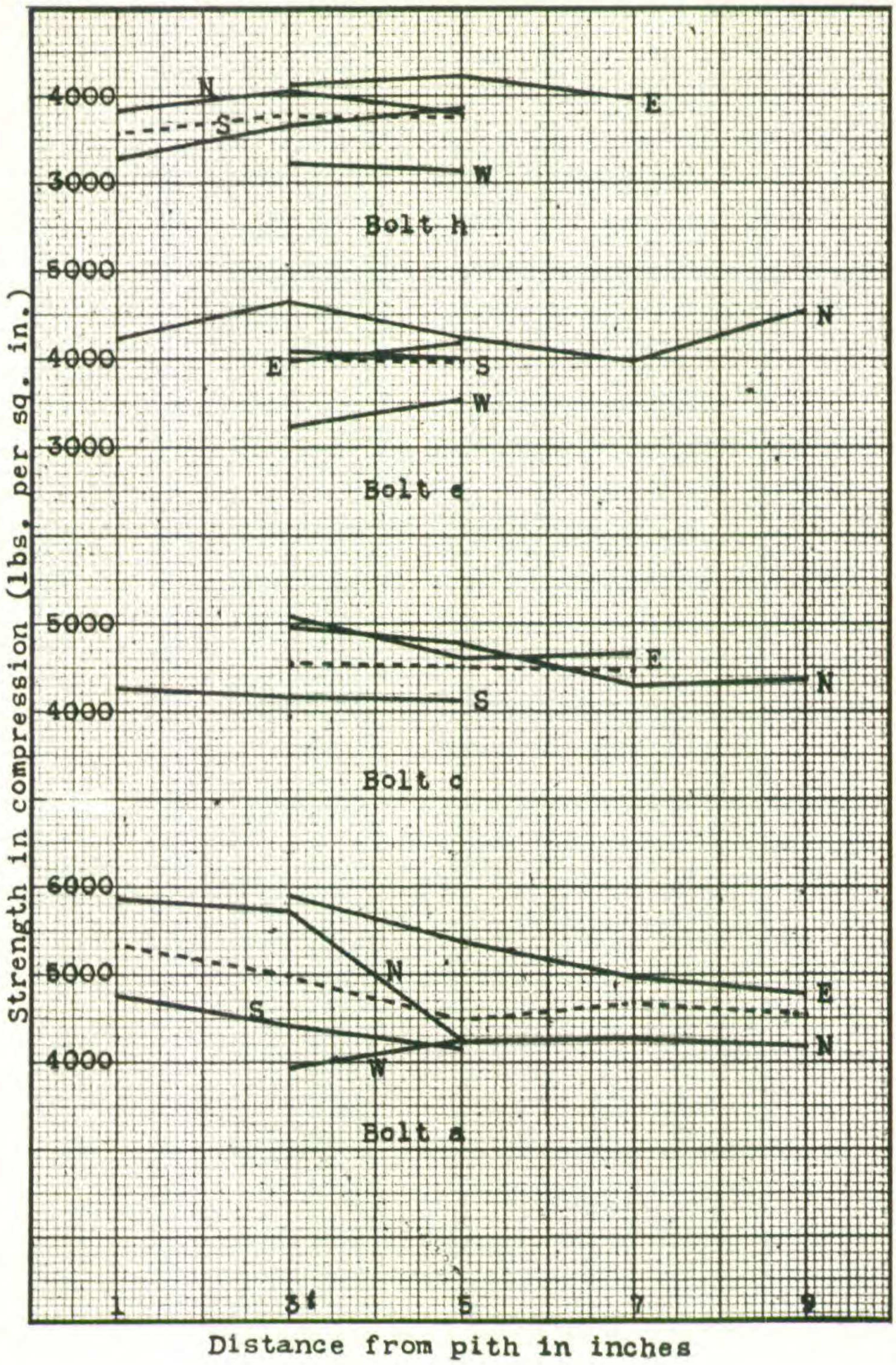

Fig. 6. Tree 3 (*Pinus echinata*, shortleaf pine), green. The solid lines represent the compression strength plotted against the distance from the pith; the broken lines, the averages of these tests. This tree was both crooked and asymmetrical, which accounts for the unequal number of tests on the different sides.

growth rings, as well as to the variations in the structure on the opposite sides. In the side having the slower growth the specimens would contain material laid down 20-40 years after that in the specimens on the opposite side, in the more rapid growth. Furthermore, areas of torquimural and crooked tracheids often occurred on one side, as opposed to straight concentrimural tracheids on the opposite side.

The *Pinus palustris* trees 4 and 6 were of very slow growth, especially for the first 2–4 inches along the radii (table I). In cutting the test sticks the pith and often the first rings containing the short tracheids, numerous resin ducts and wood rays were cut away. The result was that the maximum strength usually was within the first specimens around the pith. The average strength decreased then from this region towards the periphery of the stem (figs. 7 and 8), but occasional strong specimens occurred in the medium to outer portion of the trees. This was partly due to the impossibility of cutting directly through the pith in the crooked bolts, when the pith was thrown within a specimen which caused it to be weaker than its neighbor.

The seasoned material was of rapid-growth *Pinus Taeda* (trees 1 and 2), which increased in strength from the first formed growth rings towards the periphery of the stem. The outer sapwood in bolts *a* and *d* of tree 1 (fig. 9) had a lower strength than other specimens nearer the pith. The lower strength in the outer sapwood of tree 1 was due to the presence of a large percentage of torquimural tracheids and numerous large rays, particularly fusiform rays (tables III and IV), and not to a lower density (pl. 9, fig. 1, specimen 1aN7). The entire north and east sides of this tree, which were consistently low in strength, were composed of torquimural tracheids. There was a certain amount of this fiber throughout the stem.

Figure 11 shows the compression strength plotted against the specific gravity for the green material. The band[10] of points is thickest through the middle portion and thins out on

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[10] Instead of trying to describe the strength-density relation as a straight-line relationship, the term "band of points" is used, which includes the deviation of the individual values from a straight line as shown in figs. 11 and 12.

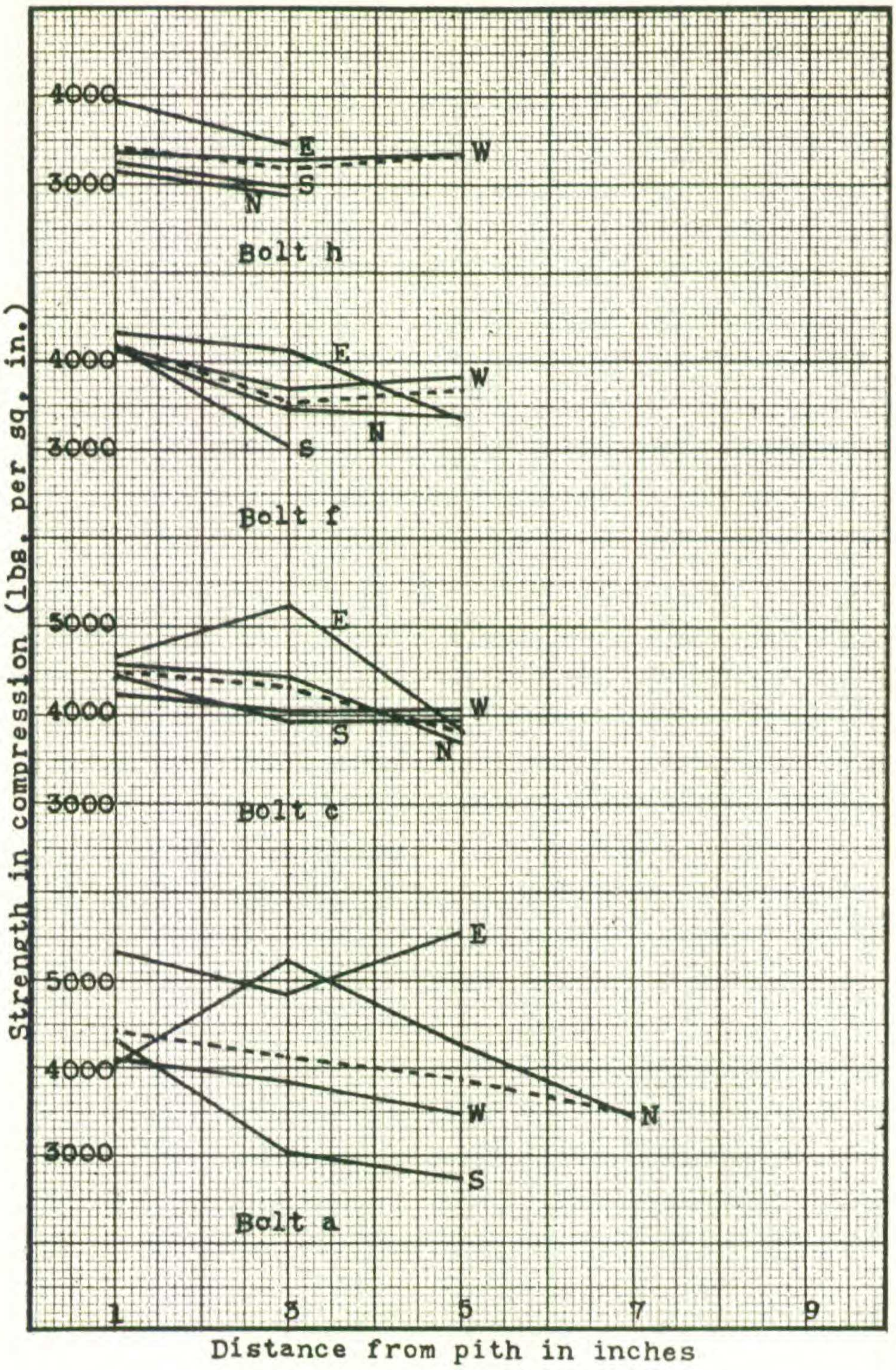

Fig. 7. Tree 4 (*Pinus palustris*, longleaf pine), green. The solid lines represent the compression strength plotted against the distance from the pith for one series of specimens on the various sides indicated; the broken lines, the averages of all tests made at the various distances along the radii.

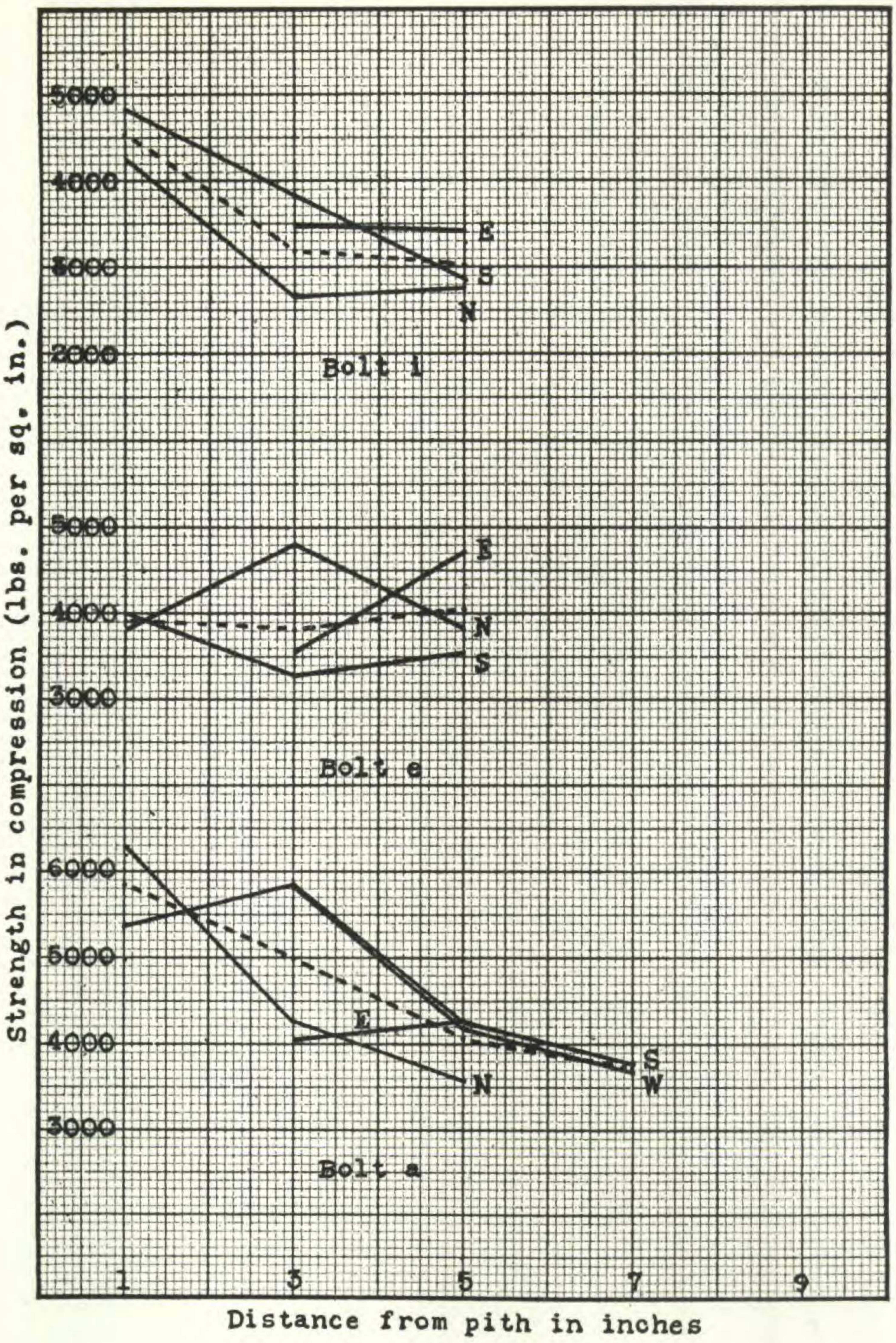

Fig. 8. Tree 6 (*Pinus palustris*, longleaf pine) green. The solid lines represent the compression strength plotted against the distance from the pith; the broken lines, the averages of all tests made in these bolts.

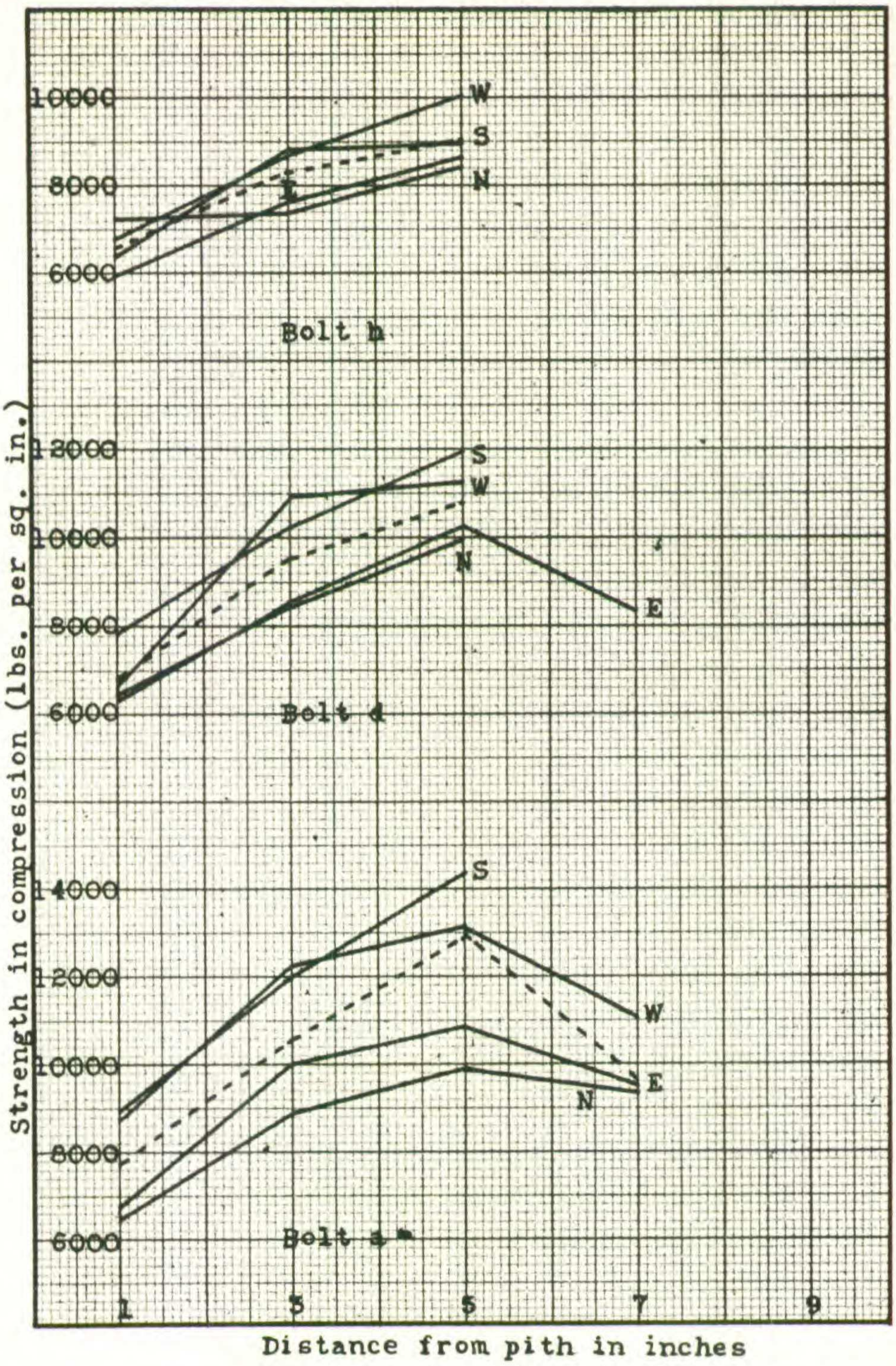

Fig. 9. Tree 1 (*Pinus Taeda*, loblolly pine), seasoned. The solid lines represent the compression strength plotted against the distance from the pith for a single series of tests; the broken lines, the averages of all tests made on each side.

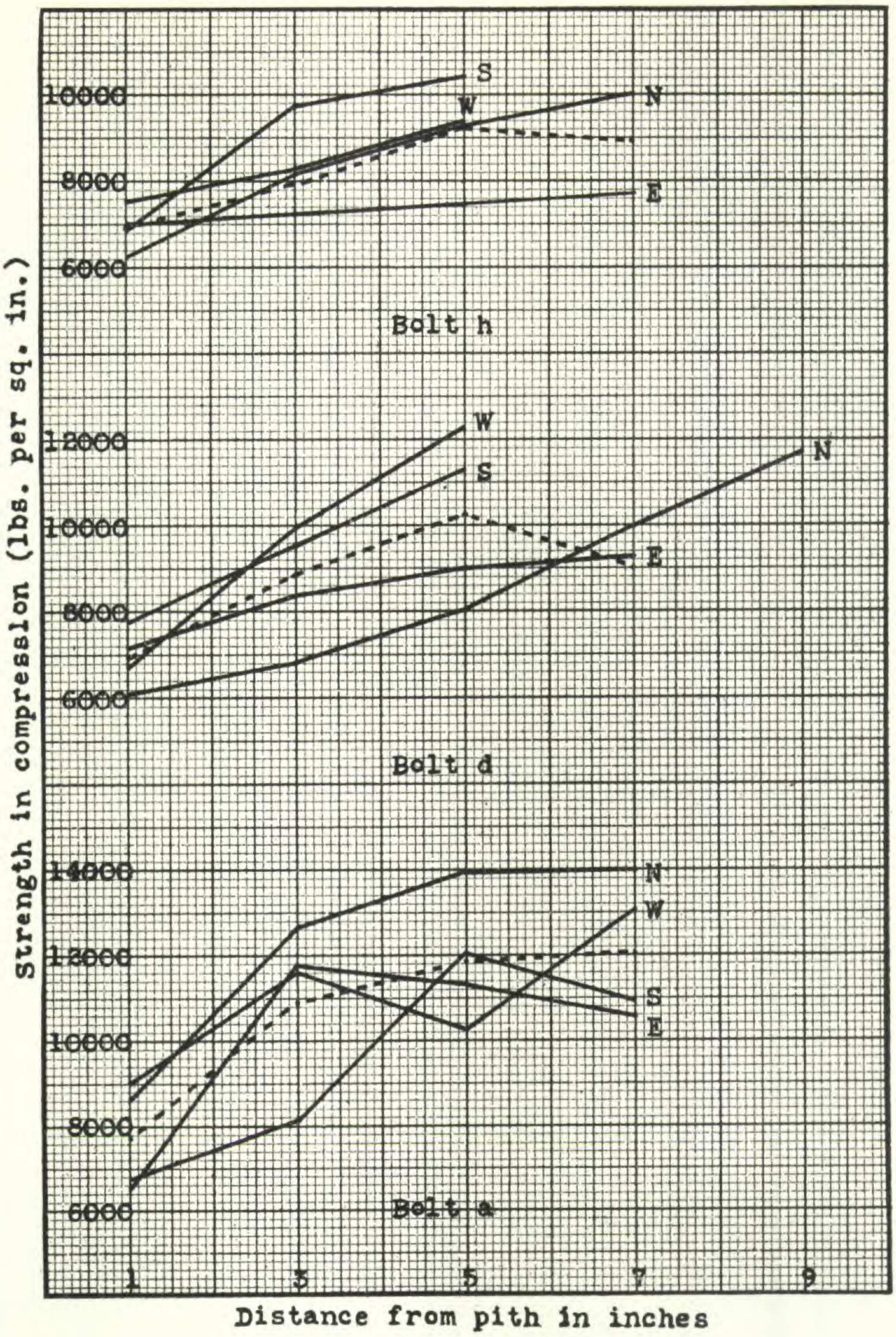

Fig. 10. Tree 2 (*Pinus Taeda*, loblolly pine), seasoned. The solid lines represent a single series of tests from the pith to the periphery of the stem on the four sides; the broken lines, the averages of all the tests made.

either side. The upper edge of the band composed of the strongest specimens per unit weight tends to form a straight line which is essentially parallel with the lower limit composed of the weakest specimens per unit weight and with the mean of all the points. In comparing the individual tests of *Pinus Taeda* and *Pinus palustris,* the former was the stronger for the lower range of specific gravity whereas for the higher range the latter was superior. *Pinus Taeda* seldom surpassed 4,000 pounds per square inch in strength, whereas the greater percentage of *Pinus palustris* was above 3,500 pounds. *Pinus echinata* covered practically the entire range of strength and density and was found in both the top and bottom edges of the band of points.

Table IX gives the strongest specimens for a given specific gravity, those found in the upper limits of the band in fig. 11, and the weakest specimens found on the opposite side of the same band. The stronger specimens had an average of 1,000 pounds greater strength than the weaker specimens, but at the same time 0.057 lower average density. The percentage of summer wood and the area taken up by resin ducts and wood rays were greatest in the weak specimens but the rings per inch and tracheid length were practically the same. In addition, a large number of the weaker specimens contained varying amounts of torquimural tracheids and all of them contained crooked or otherwise inferior tracheids (pl. 10, figs. 4 and 5), whereas the stronger specimens were made up of straight uniform concentrimural tracheids.

The seasoned material with a moisture content of from 7 to 8 per cent was about 2.6 times stronger than similar material in the green condition. Figure 12 shows the strength of the seasoned material plotted against the specific gravity. The same type of band was formed as in the green material. Table X shows the strongest and weakest specimens as found on the opposite sides of this band. The same conditions in the cells in the strong and weak material were found here as in the green material except that the torquimural cells were more pronounced, and the area taken up by resin ducts and wood rays was much higher in the weak specimens. The wood rays were

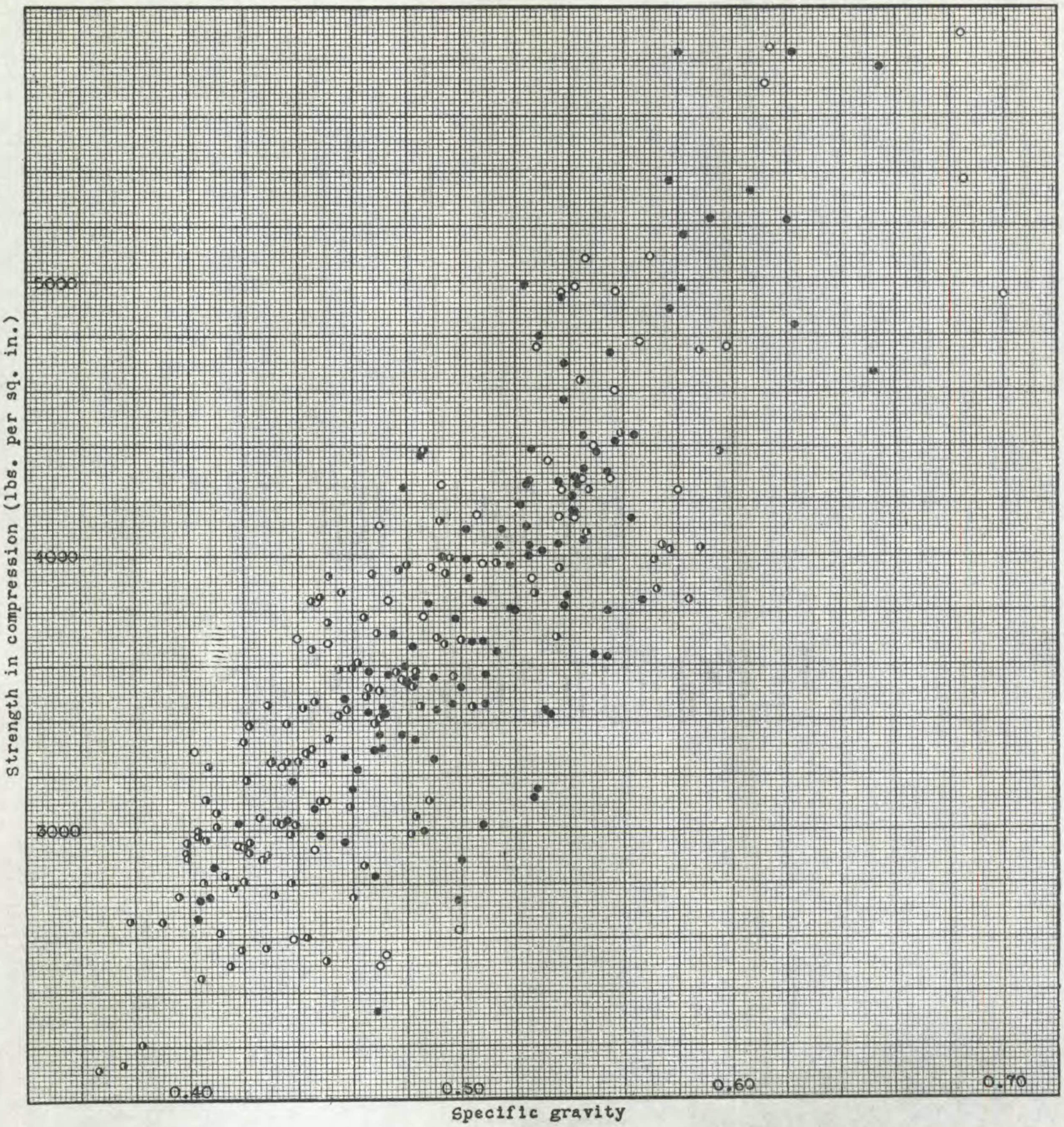

Fig. 11. The compression strength for the green material plotted against the specific gravity. *Pinus Taeda* (loblolly) is represented by a black-and-white circle; *Pinus echinata* (shortleaf), by a white circle; *Pinus palustris* (longleaf), by a black circle.

slightly larger and more numerous in areas containing a large percentage of torquimural tracheids, particularly the fusiform rays which were more effective in causing failures.

The poor differentiation of spring and summer wood in the early growth of a tree, and numerous rings in the later growth, together with the differences in thickness of cell walls in both the spring and summer wood of the different species, caused a difference in the density of the material containing an equal percentage of summer wood. *Pinus palustris* had thicker-

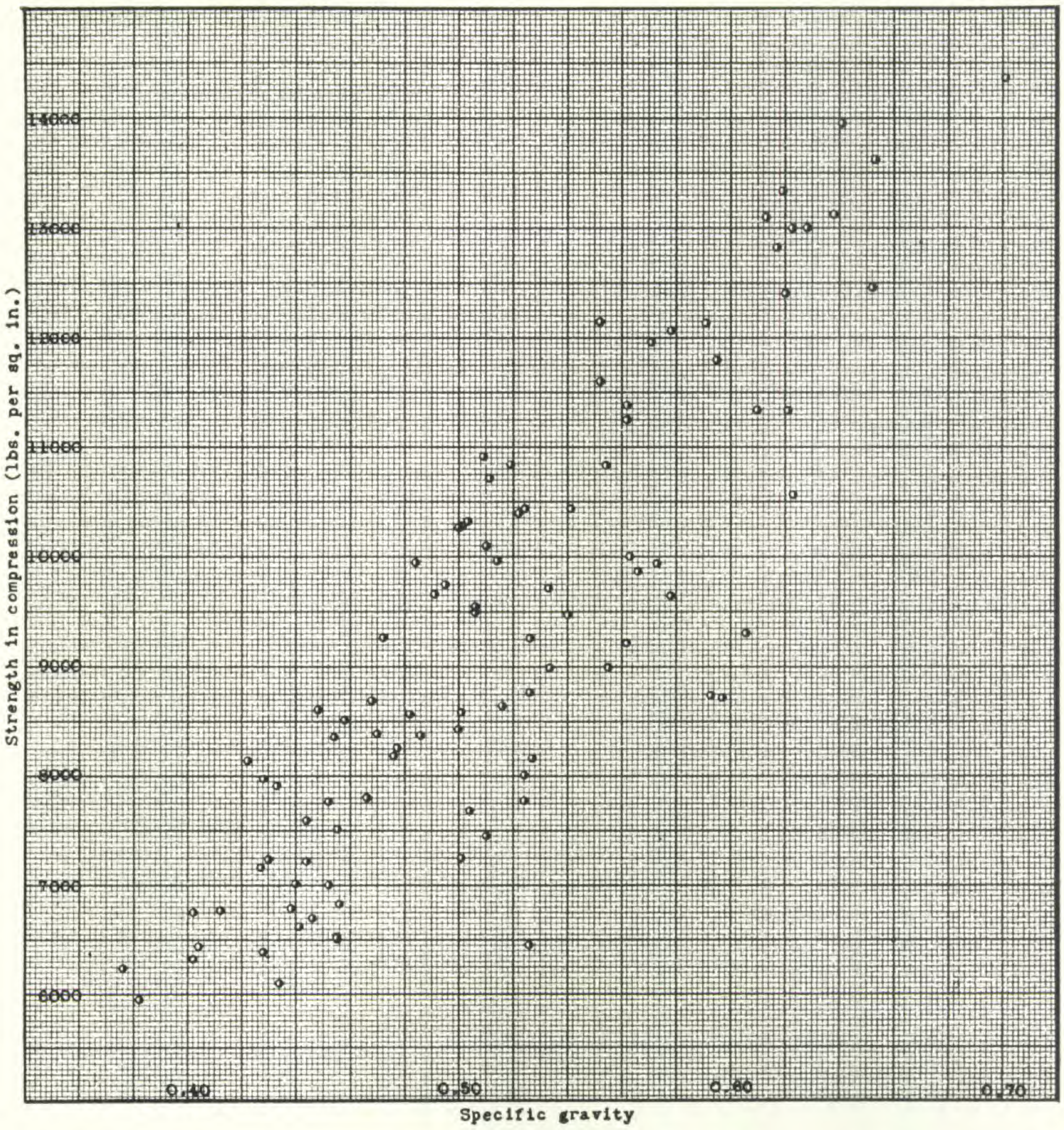

Fig. 12. The compression strength for the seasoned material, trees 1 and 2 (*Pinus Taeda*, loblolly pine), plotted against the specific gravity.

TABLE IX

THE 15 STRONGEST AND THE 15 WEAKEST SPECIMENS PER UNIT WEIGHT TAKEN FROM FIG. 11—GREEN MATERIAL

Tree and specimen No.	Compression strength in lbs. / sq. in.	Specific gravity	Percentage of resin	Percentage of moisture	Percentage of summer wood	Rings per in.	Tracheid length	Total area taken up by resin ducts and wood rays
Strongest specimens per unit weight								
6aS3	5830	0.580	8.2	35	43	39	4.7	7.88
6aN1	6300	0.620	8.6	25	47	42	4.4	7.59
6aN3	4250	0.479	4.1	91	45	12	4.7	7.24
3hS2	3290	0.402	3.9	32	14	11	3.8	7.74
3hN2	3830	0.447	3.9	29	23	11	3.8	7.07
3hE3	4110	0.470	1.0	31	41	12	4.8	7.18
3gN2	3700	0.440	2.2	29	38	10	3.9	7.07
3bS2	5080	0.546	2.0	32	55	19	4.0	7.36
3bS4	4950	0.537	2.3	54	51	19	4.2	7.36
4dN4	4370	0.485	4.3	46	43	20	5.0	7.71
4bN3	4940	0.537	4.6	39	40	23	4.7	7.99
5iN10–1	3930	0.451	1.0	34	43	8	5.1	9.59
5iN3–4	3840	0.445	1.8	35	38	10	5.0	9.41
5iN3–3	3850	0.448	4.0	32	42	7	4.4	9.20
5iE9	4390	0.486	1.5	31	45	7	4.8	9.06
Ave.	4440	0.491	3.56	39	41	16.6	4.5	8.62
Weakest specimens per unit weight								
3gS6	2630	0.499	2.9	109	46	20	5.2	7.37
3gS4	2500	0.470	2.9	47	33	18	4.8	8.11
3gS4–1	2540	0.472	3.4		32	12	4.9	7.89
3aE7	4950	0.700	2.1	30	61	9	4.3	8.62
4bN6	2330	0.469	3.5	115	41	26	5.0	8.98
4gW6	3120	0.527	3.1	109	40	21	5.1	8.69
4cN2	4670	0.652	4.5	22	40	33	4.0	8.81
4aS3	3020	0.508	2.3	124	45	19	4.7	8.65
4aN7	3420	0.531	1.9	110	45	18	5.0	9.34
4hN1	3150	0.528	23.5	23	41	22	4.0	8.95
4hN4	3630	0.554	7.4	69	57	22	5.2	8.51
5bE5	3840	0.584	1.7	35	57	5	3.7	9.26
5bN3–3	4030	0.588	1.9	34	56	5	4.6	10.63
5bS5	3880	0.572	1.9	32	63	5	4.0	9.57
5bN5	4020	0.577	2.5	36	62	5	3.7	9.53
Ave.	3448	0.548	4.37	59	48	16	4.5	8.86

walled cells with smaller lumina than either *Pinus echinata* or *Pinus Taeda*. It is indicated from fig. 13 that for a given specific gravity *Pinus echinata* must contain about 10 per cent and

TABLE X

THE 10 STRONGEST AND THE 10 WEAKEST SPECIMENS PER UNIT WEIGHT TAKEN FROM FIG. 12—SEASONED MATERIAL

Tree and specimen No.	Compression strength in lbs./sq. in.	Specific gravity	Percentage of resin	Percentage of moisture	Percentage of summer wood	Rings per in.	Tracheid length	Total area taken up by resin ducts and wood rays
Strongest specimens per unit weight								
2dS6	12150	0.552	0.9	6.9	52	6	4.9	11.17
1dW3	10920	0.509	1.1	6.9	45	10	4.3	8.74
2hN8	10720	0.511	0.9	6.6	49	7.5	5.1	10.59
1dE6	9940	0.484	1.0	7.3	47	7.5	4.8	9.49
2hN3	8140	0.422	3.9	8.0	26	2	4.0	9.73
1dE5	10260	0.500	1.4	7.3	48	7	4.8	9.94
2dS4	10830	0.519	0.5	6.2	52	5	3.7	10.97
1dE4	10320	0.503	1.1	7.3	43	10	4.3	9.03
1dS3	10280	0.501	1.2	6.6	43	6	4.0	9.16
1hE5	8610	0.448	2.2	7.9	40	9	4.9	9.21
Ave.	10217	0.495	1.4	7.0	44.5	7	4.48	9.90
Weakest specimens per unit weight								
1aN7	9300	0.606	0.9	7.1	70	6.5	4.6	11.87
1aN8	8720	0.597	2.3	7.2	65	8	4.6	12.18
1aS2	8730	0.593	3.7	6.0	38	4	2.3	10.43
1aN1	6430	0.526	5.4	6.5	38	3	2.9	10.30
2aE7	10560	0.623	1.9	7.2	65	5	4.5	11.72
2hE6	7780	0.524	2.3	7.6	56	3	4.8	11.81
2hE8	7250	0.501	2.2	7.8	40	7	5.1	11.34
2hE5	7450	0.510	1.1	7.7	32	3	4.3	11.35
2dN5	8010	0.524	1.8	6.2	45	5	4.5	10.21
2aE8	9650	0.578	1.2	7.6	65	6	4.9	11.40
Ave.	8388	0.558	2.28	7.0	51	5	4.2	11.26

Pinus Taeda 20 per cent more summer wood than *Pinus palustris*. This is further amplified by fig. 14, which shows the strength plotted against the percentage of summer wood. For the most part, each species occupied a different region of the graph, *Pinus Taeda* being weakest, *Pinus palustris* strongest, and *Pinus echinata* intermediate for a given percentage of summer wood. The overlapping of the species was greatly influenced by the variations in strength in a given species due to inferior fibers as described for the material represented in figs. 11 and 12. When the strength of a single species was plotted against the percentage of summer wood, however, there was less spread of points and a band similar to the specific gravity-strength relations was obtained (fig. 15). Since the specific gravity (when corrected for resin content) is a more accurate measure of the mass represented, there was less spread in the points when the specific gravity was plotted against the strength (compare figs. 12 and 15). Essentially the same specimens were found in the upper and lower limits of the bands in these two figures.

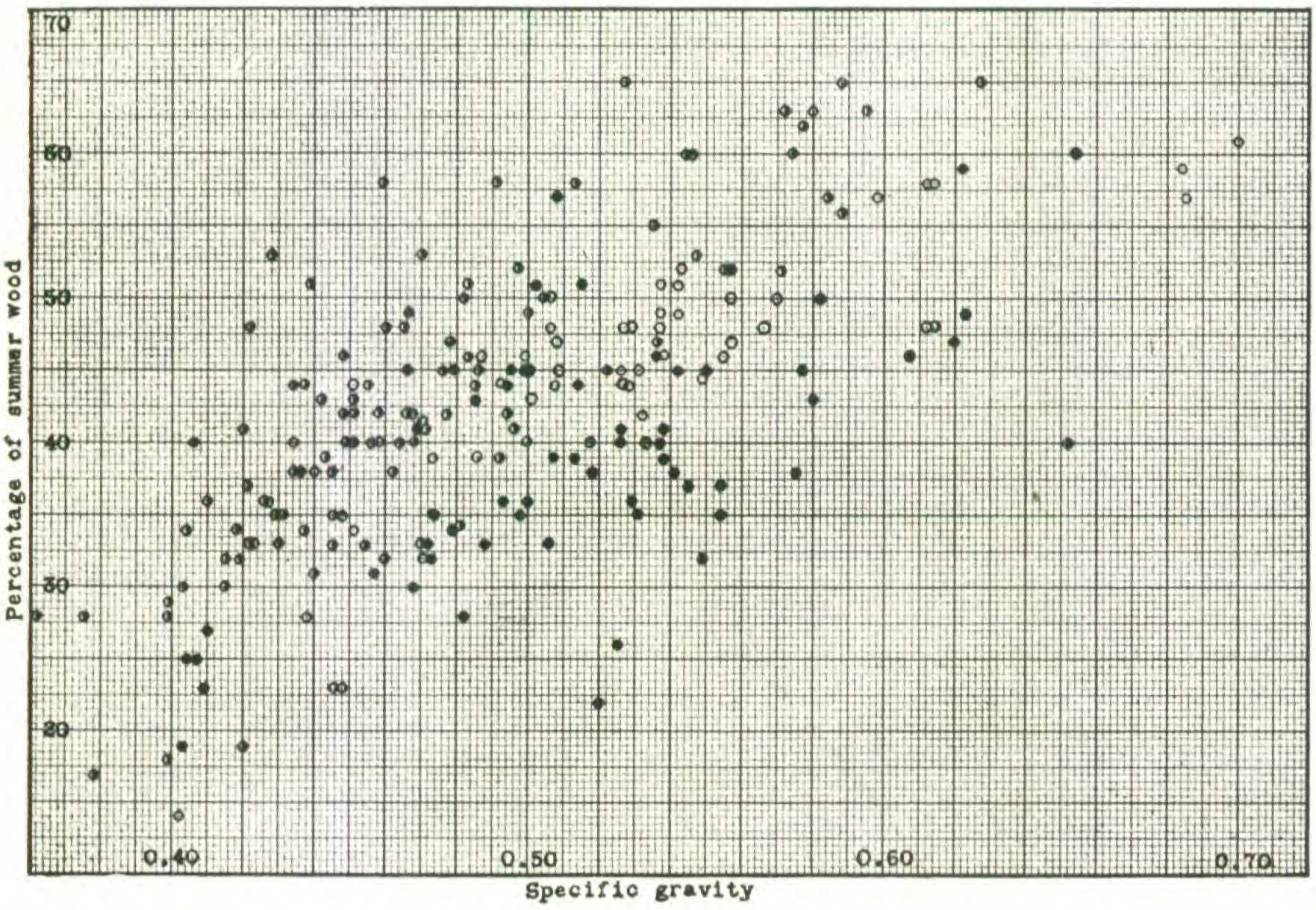

Fig. 13. The percentage of summer wood plotted against the specific gravity. *Pinus Taeda* (loblolly pine), black-and-white circle; *Pinus echinata* (shortleaf pine), white circle; *Pinus palustris* (longleaf pine), black circle.

DISCUSSION

The specific gravity of clear specimens of southern yellow pine wood is not an accurate measure of its strength, and the percentage of summer wood, without regard for the density of the different species, shows even greater variations under present specifications. Resins increase the specific gravity,

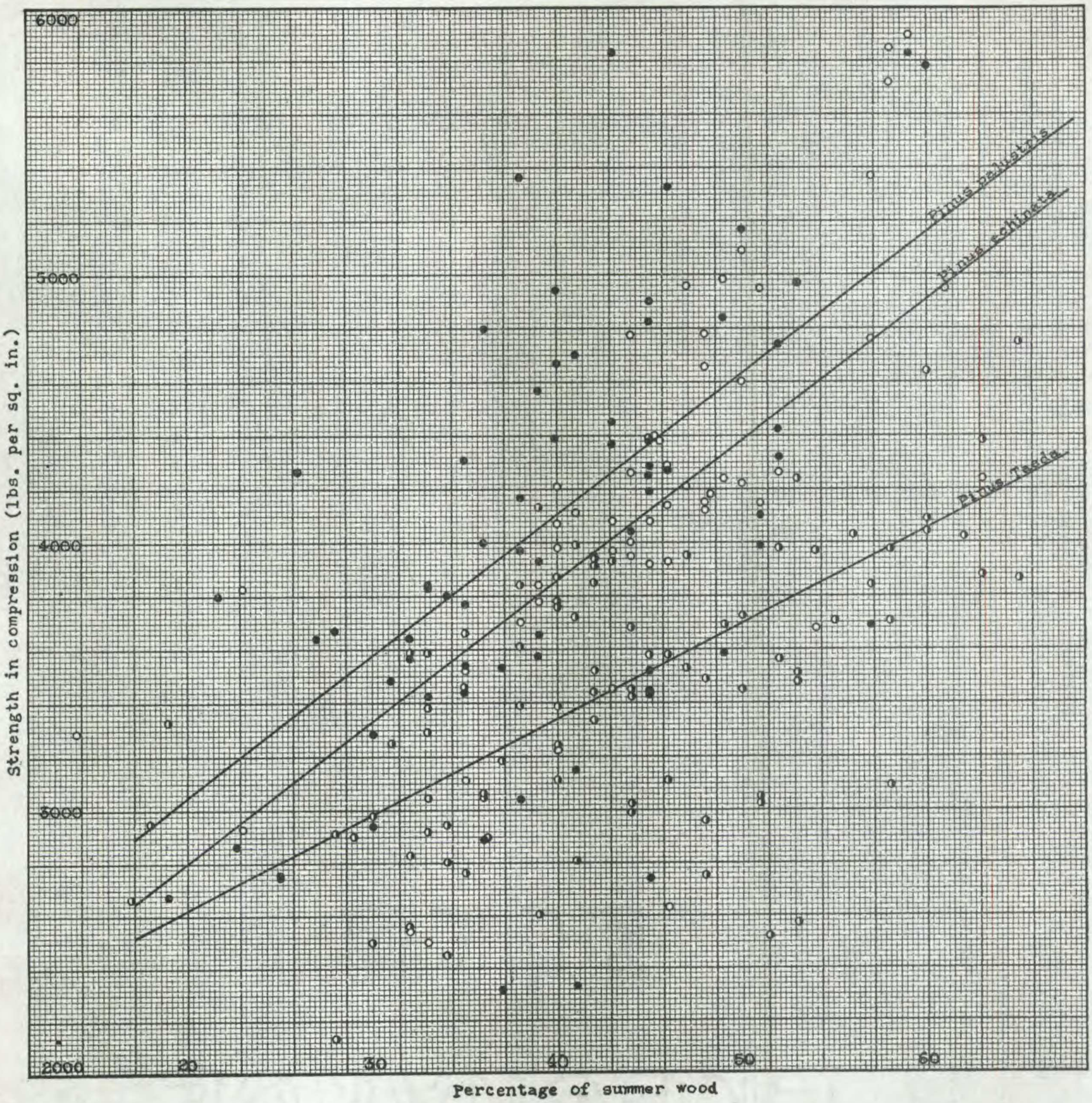

Fig. 14. Trees 5 and 7 (black-and-white circle, *Pinus Taeda*), tree 3 (white circle, *Pinus echinata*), trees 4 and 6 (black circle, *Pinus palustris*), green. The compression strength plotted against the percentage of summer wood. The lines represent the averages of the various species as indicated. The wide spread of points may be largely attributed to the differences in density of the summer wood in the three species as shown in fig. 13.

with little or no effect upon the strength. Although the wider variations were eliminated by correcting the specific gravity for benzol-soluble compounds, there were still variations of from 1,500 to 2,000 pounds per square inch for practically the entire range of specific gravity in the green material. In spite of these variations the strength of the best material varied directly with the first power of the density, and the average strength of the different species agreed very well with the averages reported by Newlin and Wilson ('17) for the same

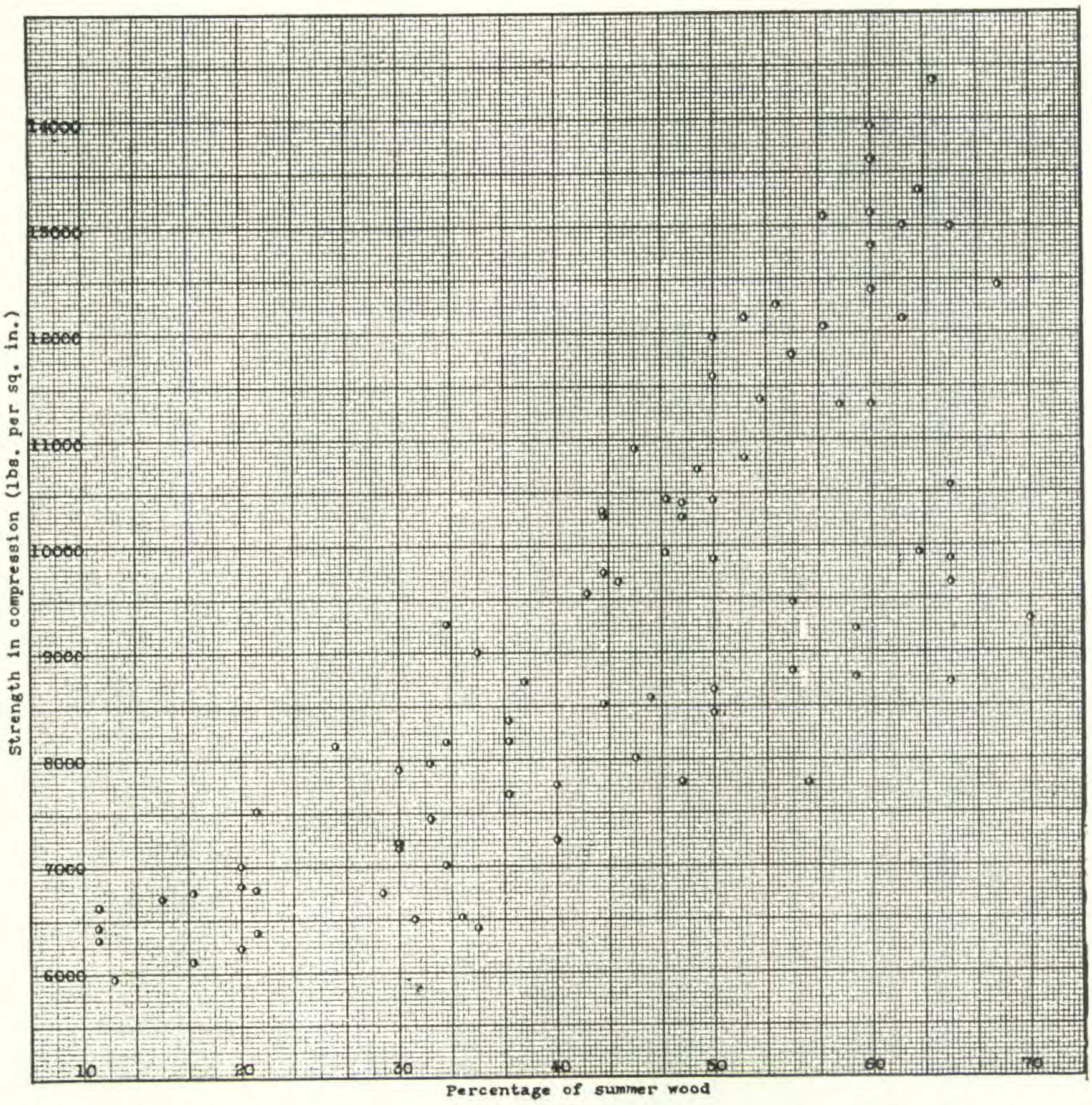

Fig. 15. Trees 1 and 2 (*Pinus Taeda*), seasoned. The compression strength plotted against the percentage of summer wood. Note the close agreement of this figure with that of fig. 12, which represents the compression strength plotted against the specific gravity for the same material.

species, with the exception of tree 3, *Pinus echinata,* which was unusually strong for its species. There was an increase of about 1,300 pounds per square inch for an increase of 0.1 in specific gravity in the green material and about 3,000 pounds in the dry material if only the most perfect specimens were considered. When the increase in strength for the changes of moisture was accounted for, both the green and seasoned material showed essentially the same relations of density and strength.

Since the variable due to moisture content was eliminated by using only green material (that with a moisture content above the fiber-saturation point) and specimens of a similar moisture, and since the absolute density of the wood substance was constant, the variations in strength were attributed to the differences in structure. The anatomical structure of the southern yellow pines is simple and has been described by Mohr and Roth ('97) and others. The woody cylinder or xylem is composed primarily of tracheids with occasional groups of wood parenchyma. An anastomosing system of resin canals and the wood rays make up the remainder of the structure.

In order to make any correlation between the strength and the structure, it was necessary to evaluate the strength on a unit-weight basis known as the specific gravity. The short-fibered material in the first few growth rings was weak, being less than half as strong in certain cases as the longer-fibered material farther out in the tree, but it was also much lighter. The very first rings, however, were not so strong in proportion to their density as the best material containing the longer tracheids. On the other hand, they were not so weak in proportion as the poorest material, which also contained long tracheids. The weakness of this short-fibered material was apparently due to the large number of resin canals and wood rays which interrupted the unity of the material. In very slow-growth trees this area may be neglected but in rapid-growth material there may be a difference of 50 to 100 per cent in strength along a radius of from 6 to 8 inches (table VIII, compare specimen 1dS2 with 1dS6 and 2aN2 with 2aN5).

As the tracheids increased in length the density also increased, but the latter reached a maximum between the ages of 40 and 100 years (also Mohr and Roth, '97), after which it declined more or less rapidly, whereas the tracheid length sometimes fluctuated although with little regular reduction in length. The maximum strength was found to be in this high density material in the intermediate zone, but the strength was often much lower than was indicated by the density. It was for the most part this high-density material that showed the greatest fluctuation in strength per unit weight.

Comparing the extremes in strength per unit weight, there was little difference in the length of the tracheids and rings per inch in the strongest and weakest specimens of the green material, but there were differences in the percentage of area taken up by resin ducts and wood rays and particularly in the contour of the cells and the structure of the cell walls. The percentage of area taken up by the wood rays and resin ducts was noticeably greater in the weak specimens of the seasoned material, but it is evident that these factors (fiber length, resin canals, and wood rays) were not entirely responsible for the wider variations in strength although it was indicated that they contributed to it. The fact that the tracheids buckled away from the rays (pl. 13, figs. 3 and 4) indicated that an excess of rays would be weakening. Furthermore, areas containing a high percentage of torquimural tracheids had a greater percentage of rays than the other material.

There was no direct correlation between the number of rings and the strongest or weakest specimens per unit weight, but the greatest strength for a given tree was usually found in the intermediate growth, while low density and low strength were associated with extremely rapid or slow growth. The weaker specimens per unit weight had a much higher percentage of summer wood than the stronger ones regardless of species, but in the material containing straight uniform tracheids with concentric laminae (concentrimural tracheids) the strength increased with the summer wood within a given species. In general, however, for a given specific gravity, *Pinus echinata* contained 10 per cent and *Pinus Taeda* 20 per cent more summer wood than *Pinus palustris,* and similarly for a given strength there was a greater percentage of summer wood in *Pinus Taeda* and *Pinus echinata* than in *Pinus palustris.* From this it is concluded that for the strongest material per unit weight one must choose medium to low density *Pinus Taeda* and medium to high density *Pinus palustris.* This is borne out by fig. 11, which shows that for the lower density material *Pinus Taeda* is the strongest, whereas for the high density material, *Pinus palustris* and *Pinus echinata* are superior. *Pinus echinata* was not sufficiently well represented here to justify any definite statement as to how it would fit into this relationship.

Since the poorer material was not confined to the very dense or very light wood and since the greater variations in strength were not entirely due to the length of the tracheids nor the wood rays and resin canals, the cause must be sought in the general contour of the cells and the structure of the cell walls. Weakness was associated with torquimural, crooked, and otherwise deformed tracheids, although the walls of the latter were often made up of the usual concentric laminae. The crooked fibers tended to buckle more readily than the straight ones, which caused the material to be considerably weaker than was indicated by its density.

Sonntag ('04) found that the tensile strength of ordinary wood was from 25 to 50 per cent greater than that of compression wood (torquimural cells). He also stated that the compression side of the tree had a greater resistance to compression than the tension side due to the thicker walls, which gave a greater resistance to bending in that direction. He did not take into account the great differences in density, however, which more than offset the increase in strength or stiffness. Jaccard ('28) observed that compression wood contained a higher percentage of lignin than normal wood, as did Dadswell and Hawley ('29) for compression wood of Sitka spruce. Koehler ('33) reported that compression wood in the green condition was low in stiffness and on a unit-weight basis was inferior in all strength qualities. When seasoned the differences were much greater, and the compression wood was very brash in tension.

The torquimural tracheids, with an entirely different wall structure from the concentrimural cells, were brash and had from 1,500 to 2,000 pounds less strength per unit weight in the green condition and from 2,000 to 3,500 pounds less in the seasoned condition than the material made up of straight cells. The increase of strength with dryness was not so great in the specimens containing large quantities of torquimural cells, due primarily to the checking of the individual cell walls and to the internal stresses caused by unequal shrinkage. The middle lamella had the same concentric arrangement as the concentrimural cells and in most cases the latter were interspersed with the torquimural tracheids. This condition, together with the great differences in the pitch of the spiral of the laminae (and micells which are contained in the laminae) in adjacent torquimural cells, was responsible for these internal stresses. The low strength of the torquimural tracheids in the green condition was caused by two factors: (1) the structure of the cell walls, and (2) the poor union between the cells, due to the rupture of the middle lamellae forming interstitial spaces.

The great differences in strength per unit weight of green southern yellow pine may be largely attributed to the variations in the straightness of the tracheids, disruption of the middle lamellae forming interstitial spaces, the structure of the cell walls, and, to a certain extent, to the variations in resin ducts and wood rays (particularly fusiform rays). It must be borne in mind, however, that the effects of these factors were accumulative, that no single one of them alone, with the possible exception of the structure of the cell wall, was responsible for the wider variations in strength.

Due to the fact that one or more of the above factors was present and effective to a certain extent in any given sample of wood, it is evident that the density plotted against the strength is not a straight-line relation but a band relation, of which the more perfect specimens will be found in the upper portion and the spread depends upon the diversity of the material.

Although variations of from 50 to 100 per cent in strength of small clear specimens in southern yellow pine timber taken from the same tree and similar but smaller variations in strength of specimens of the same density may be expected, this need not be an unsurmountable barrier to the grading and uses of this material for special designs. The knowledge of the variations in density and strength in the cross-section in relation to the age and growth rate of the tree and at the different heights in the tree will make it possible to cut timbers of a structural size without serious differences in strength. The knowledge of the differences in specific gravity for a given percentage of summer wood in the various species will make it possible to evaluate the strength more correctly on the basis of percentage of summer wood. The serious defects in the form of crooked fibers and torquimural tracheids are visible in dressed materials and may be eliminated in pieces of small dimensions. A more complete knowledge of the extent and distribution of these major defects in the virgin and second-growth timber of a given species and in different species of wood used for structural timbers will make it possible to modify the grading rules to take care of these variabilities.

The bending strength and elastic properties of this material, together with a more complete treatment of the compression strength as related to engineering practice, will be given in a future paper.

SUMMARY

1. Compression tests parallel to the grain, together with a study of the physical properties and microscopic structural features, were made on small specimens of clear wood taken from seven southern yellow pine trees cut in Walthall County, Mississippi. Four of these trees were *Pinus Taeda,* one was *Pinus echinata,* and two were *Pinus palustris.*

2. The fiber-saturation point as measured by the electro-conductivity method was 22.5 ± 1 per cent.

3. The absolute density of the wood substance was 1.52 as compared with water at 4° C.

4. The percentage of benzol-soluble materials designated as resins varied from 0.4 to 21 per cent in *Pinus Taeda,* with an average of 2.3 per cent, from 0.9 to 6.4 per cent in *Pinus echi-*

nata, with an average of 2.5 per cent, and from 0.9 to 29.1 per cent in *Pinus palustris,* with an average of 5.6 per cent.

5. The rate of growth varied from 1¾ to 25 rings per inch in *Pinus Taeda,* from 5 to 21 rings in *Pinus echinata,* and from 9 to 55 rings per inch in *Pinus palustris.* The first-formed rings of the *Pinus Taeda* trees were very broad, the growth rate decreasing with an increase in the age of the tree, whereas in the *Pinus echinata* and *Pinus palustris* trees the first 2 to 4 inches from the pith were of very slow growth, the growth rate increasing with the age of the trees.

6. The percentage of summer wood, and thus the density, decreased from the region of the base of the tree towards the crown. In general, the density increased from the first growth ring to a maximum in the region of the 100th ring and declined from this point towards the periphery of the stem.

7. For a given specific gravity, *Pinus echinata* contained about 10 per cent, and *Pinus Taeda* 20 per cent, more summer wood than *Pinus palustris.* The differences in density were due to the variations in thickness of the cell walls.

8. The percentage of area taken up by resin ducts was greatest in *Pinus Taeda* and least in *Pinus echinata.*

9. The wood rays decreased in number and increased in size from the pith to the periphery of the stem in all three species. They occupied slightly more area at the base of the tree, decreased somewhat at the higher levels, and again increased to a second maximum at the top. They were largest in the rapid-growth *Pinus Taeda* and smallest in *Pinus echinata.*

10. The tracheid length increased rapidly through the first 10 growth rings and more slowly through the remaining rings. Slight fluctuations in length were observed in the outer portions of the older trees. The tracheid length increased from the stump level towards the top of the tree, at least for the first few feet.

11. Torquimural tracheids are defined as cells with or without interstitial spaces, moderately to very dense, the secondary thickening of the individual cell wall being sharply differentiated from the primary wall by its radial bands or laminae which lie in a spiral around the cell. Torquimural tracheids

were not confined to the leaning side of the tree, but they occurred also on opposite sides of the same cross-section.

12. Failure in compression was accompanied by buckling of the tracheids in the direction of a tangent to the annual rings. The buckling cells separated from each other at the interfaces of the middle lamella and the secondary thickenings. In the concentrimural cells, buckling was accompanied by a folding of the wall on the inner side of the curve, whereas in the torquimural cells, when buckling occurred, it was usually accompanied by a shredding of the laminae, although the tracheids often settled by folding upon themselves or broke off short.

13. The compression strength was roughly proportional to the specific gravity, but there were variations of from 40 to 70 per cent in strength (based upon the minimum strength) for a given specific gravity. Due to the numerous factors affecting strength, the strength-density relationship is better expressed by a band than a straight line. The strength decreased from a maximum in the lower 12 to 16 feet of the tree towards the crown regardless of species. It increased from the region of the pith towards the periphery of the stem. The strength reached a maximum in the outer sapwood of the younger *Pinus Taeda* trees, and from 7 to 11 inches from the pith in the older *Pinus Taeda* tree after which it declined rapidly to a minimum in the outer sapwood, whereas it decreased from the first specimens around the pith towards the periphery of the stem in the *Pinus echinata* and *Pinus palustris* trees.

14. For the low-density material, *Pinus Taeda* had a greater strength per unit weight, whereas for the high-density material *Pinus palustris* and *Pinus echinata* were superior.

15. The strongest wood per unit weight contained straight concentrimural tracheids with few interstitial spaces, whereas wood which was very weak in relation to its density was associated with crooked and torquimural tracheids. The accumulative effects of numerous wood rays and resin ducts also contributed to the weakness of the material.

16. Since the material containing extremely crooked fiber and the more pronounced torquimural tracheids can be dif-

ferentiated in the dressed condition from the better grade of lumber, the above data will aid the man of industry in selecting timbers for special designs. More data of this type will facilitate the formulation of grading rules and make it possible for lumber companies to standardize their products.

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Explanation of Plate

PLATE 9

Three test specimens from each of the seven trees showing some of the variations in growth rate and percentage of summer wood.

Fig. 1. From tree 1 (*Pinus Taeda*, loblolly pine), showing the extreme range in percentage of summer wood. Specimen 1aN7 at the extreme left is composed almost entirely of torquimural tracheids.

Fig. 2. From tree 2 (*Pinus Taeda*, loblolly pine), showing the great variation in growth rate and the poor differentiation of spring and summer wood in specimen 2hS1 at the extreme right.

Fig. 3. From tree 5 (*Pinus Taeda*, loblolly pine), showing the differences in growth rate and percentage of summer wood in the immediate vicinity of the pith (specimen 5iS1), the intermediate zone (5bN12), and in the outer sapwood (5bN3–5). Note the V-shaped markings in 5bN12.

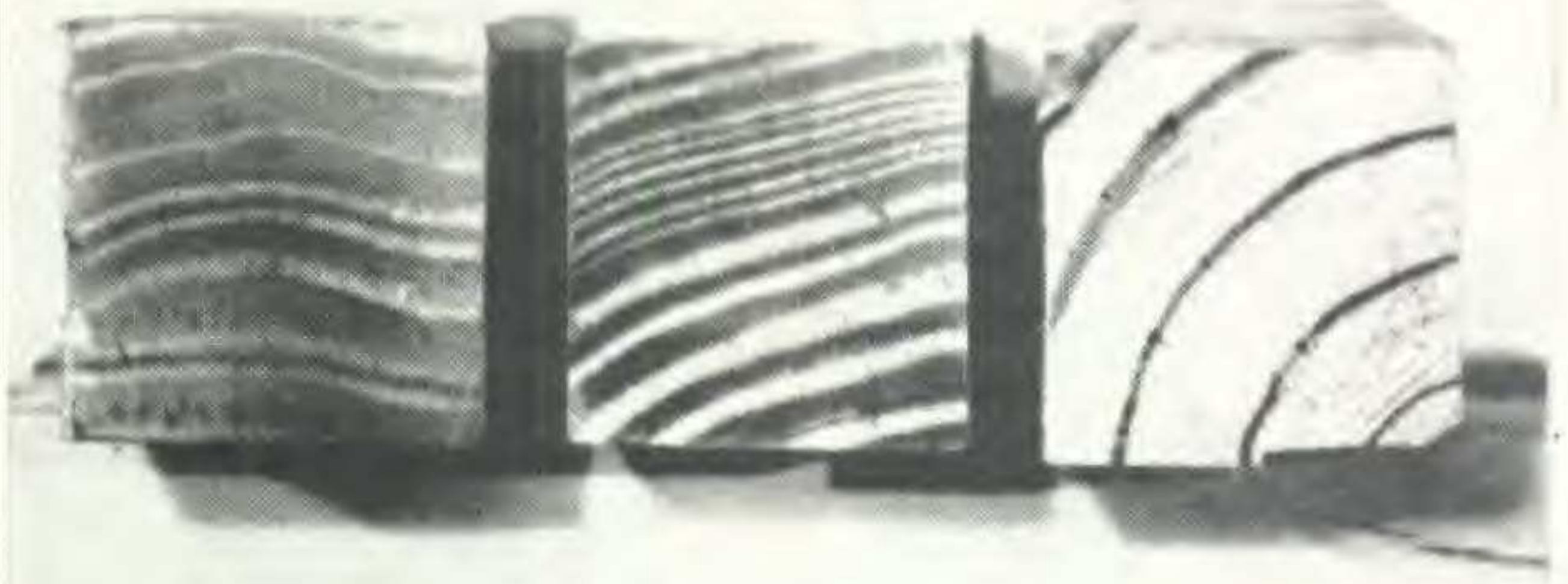
Fig. 4. From tree 7 (*Pinus Taeda*, loblolly pine), showing the major variations in growth rate and percentage of summer wood. Specimen 7gE3 on the extreme right has poor differentiation of spring and summer wood and contains a certain amount of torquimural tracheids.

Fig. 5. From tree 3 (*Pinus echinata*, shortleaf pine), showing the differences in percentage of summer wood and growth rate in the immediate vicinity of the pith at the different heights in the tree as shown in 3aS2 and 3fN1.

Fig. 6. From tree 4 (*Pinus palustris*, longleaf pine), showing variations in growth rate and the irregular rings containing torquimural tracheids as seen in 4cS5.

Fig. 7. From tree 6 (*Pinus palustris*, longleaf pine), showing variations in growth rate and percentage of summer wood. Note the broad rings of summer wood in 6eE5 which are composed largely of torquimural tracheids.

Specimen 1aN7 of fig. 1 is representative of the material found in the weakest specimens per unit weight of the seasoned material, and 4cS5 of fig. 6, of the green material.



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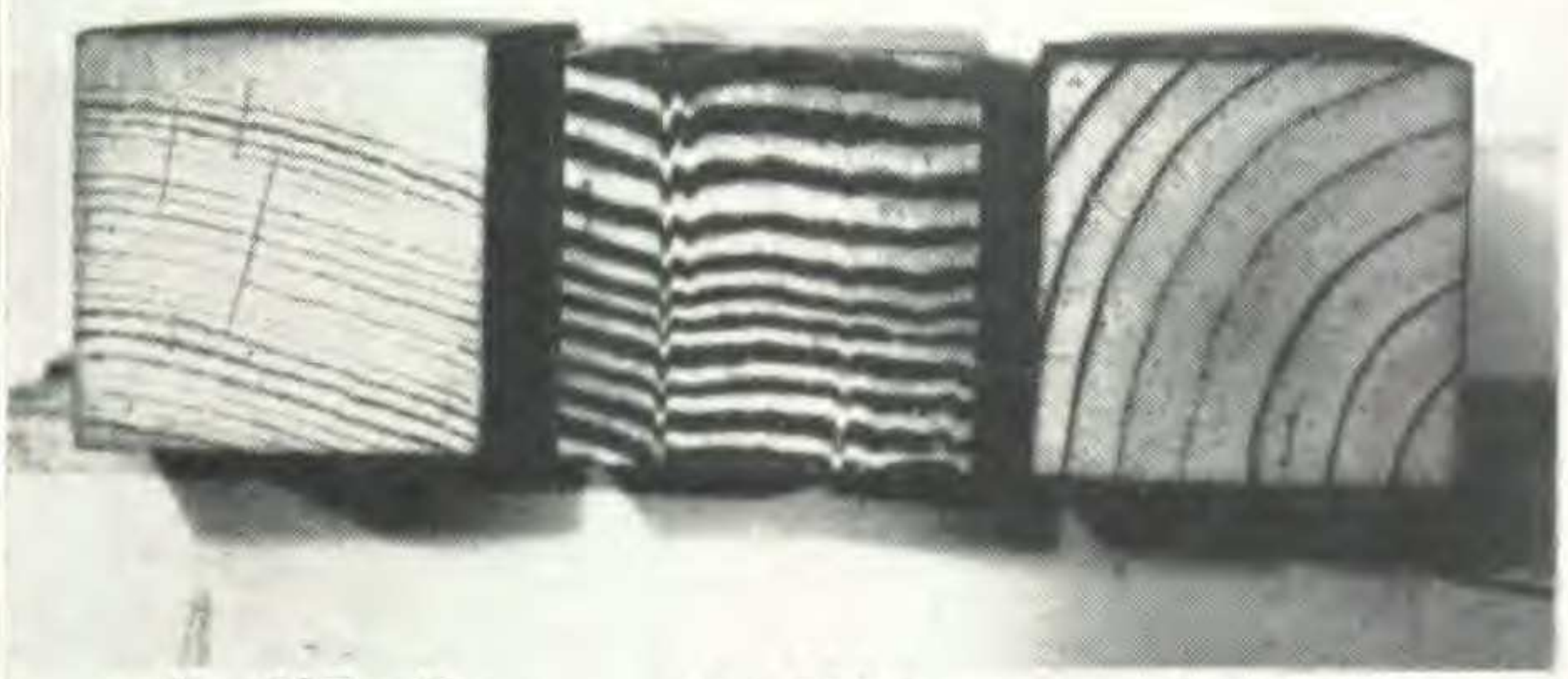

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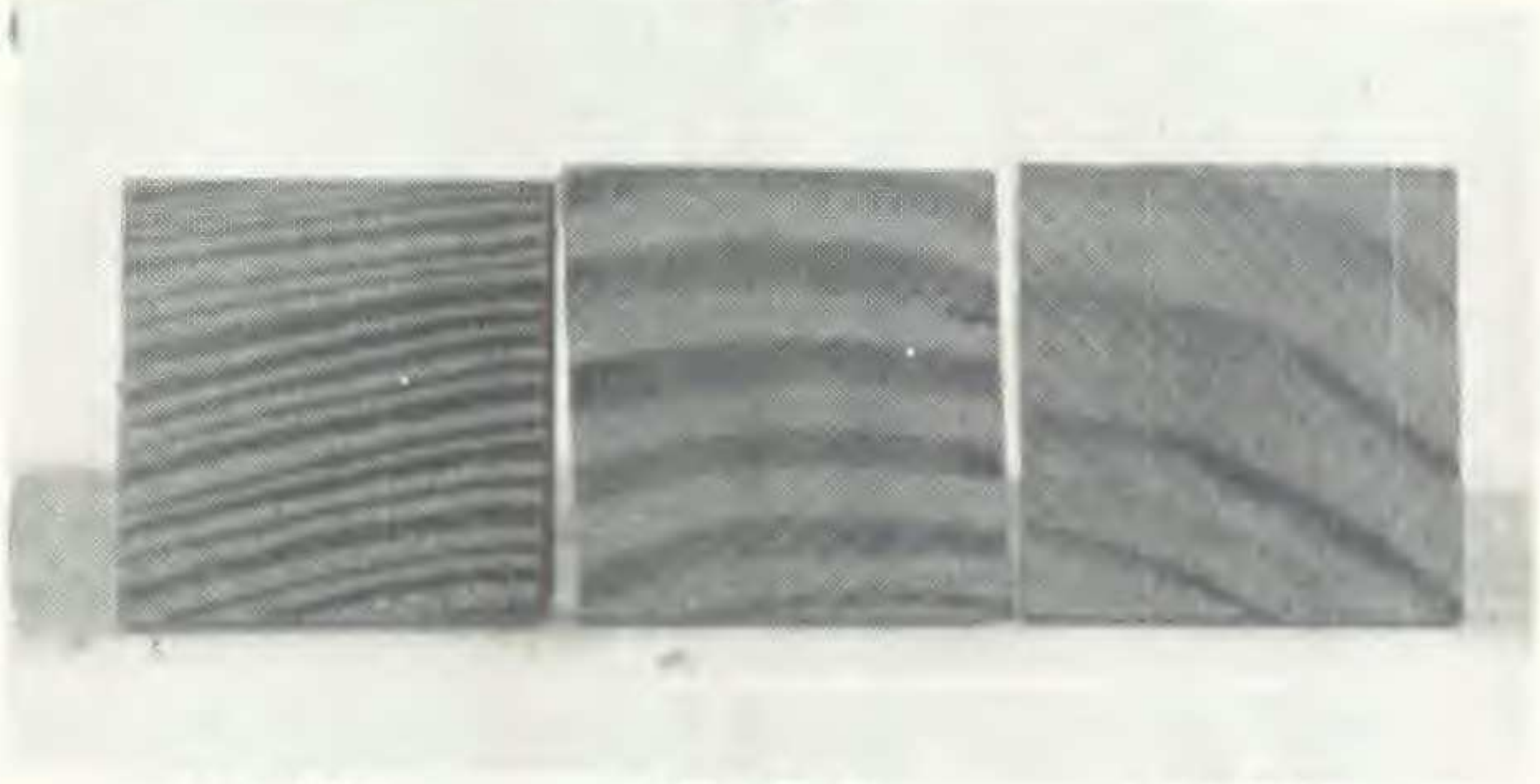

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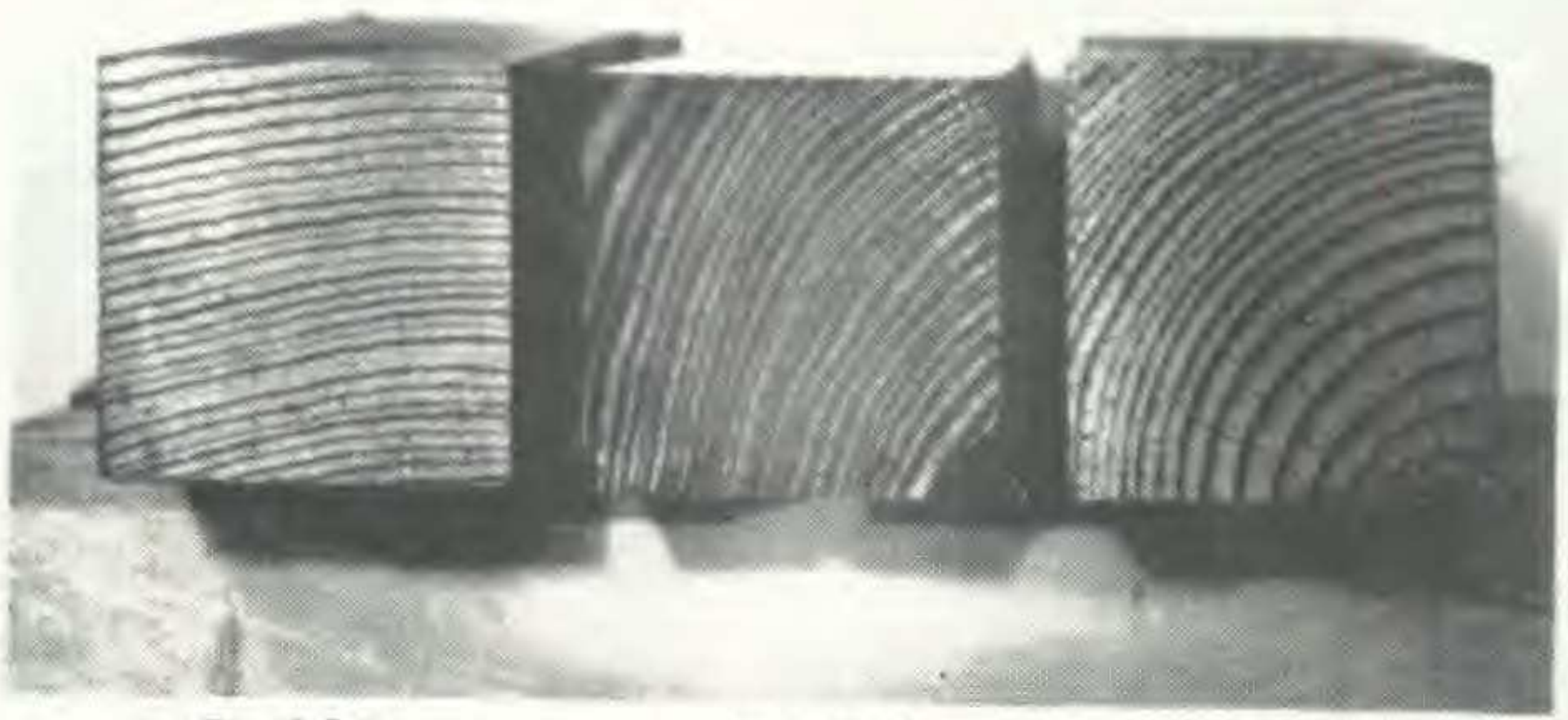

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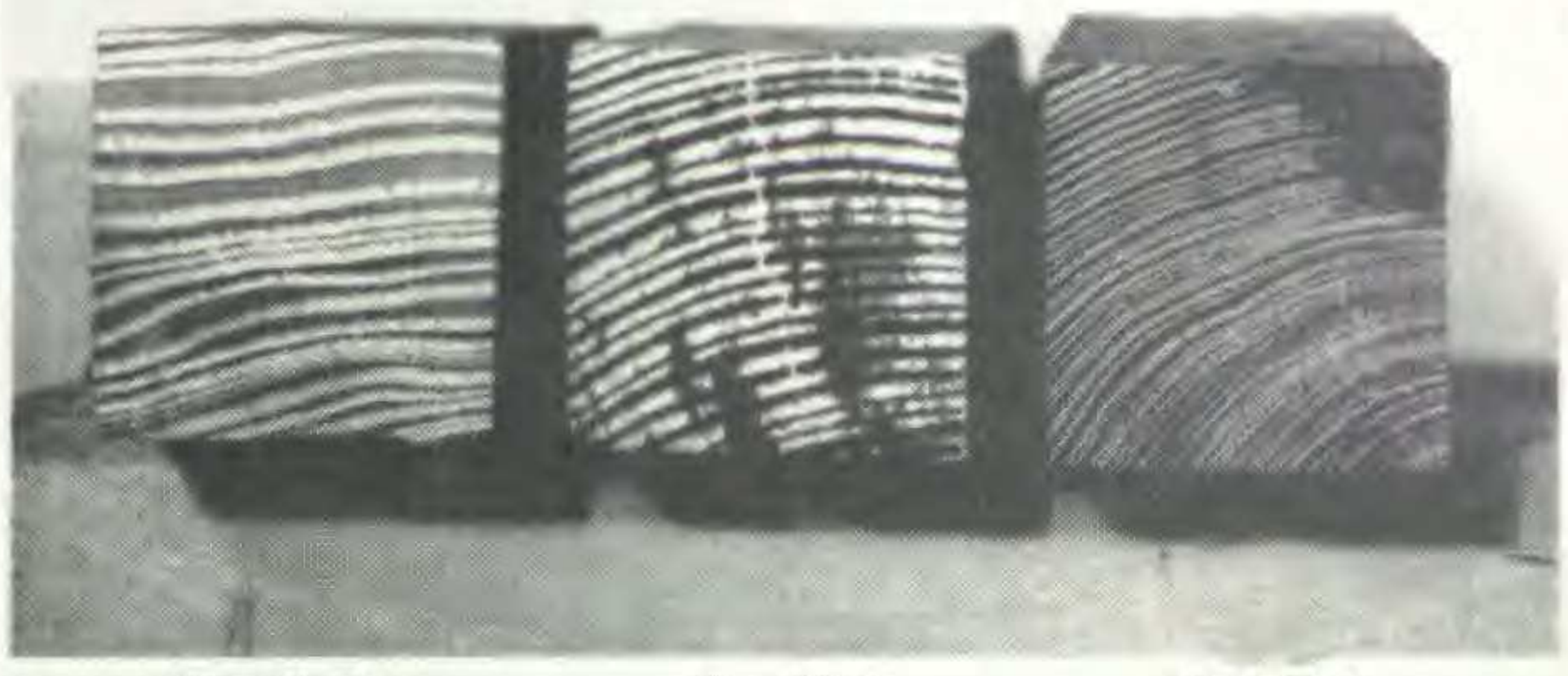

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BERKLEY—SOUTHERN PINE

Explanation of Plate

PLATE 10

Fig. 1. A cross-section of the spring-wood portion of an annual ring showing the distribution of the resin ducts. × 13.

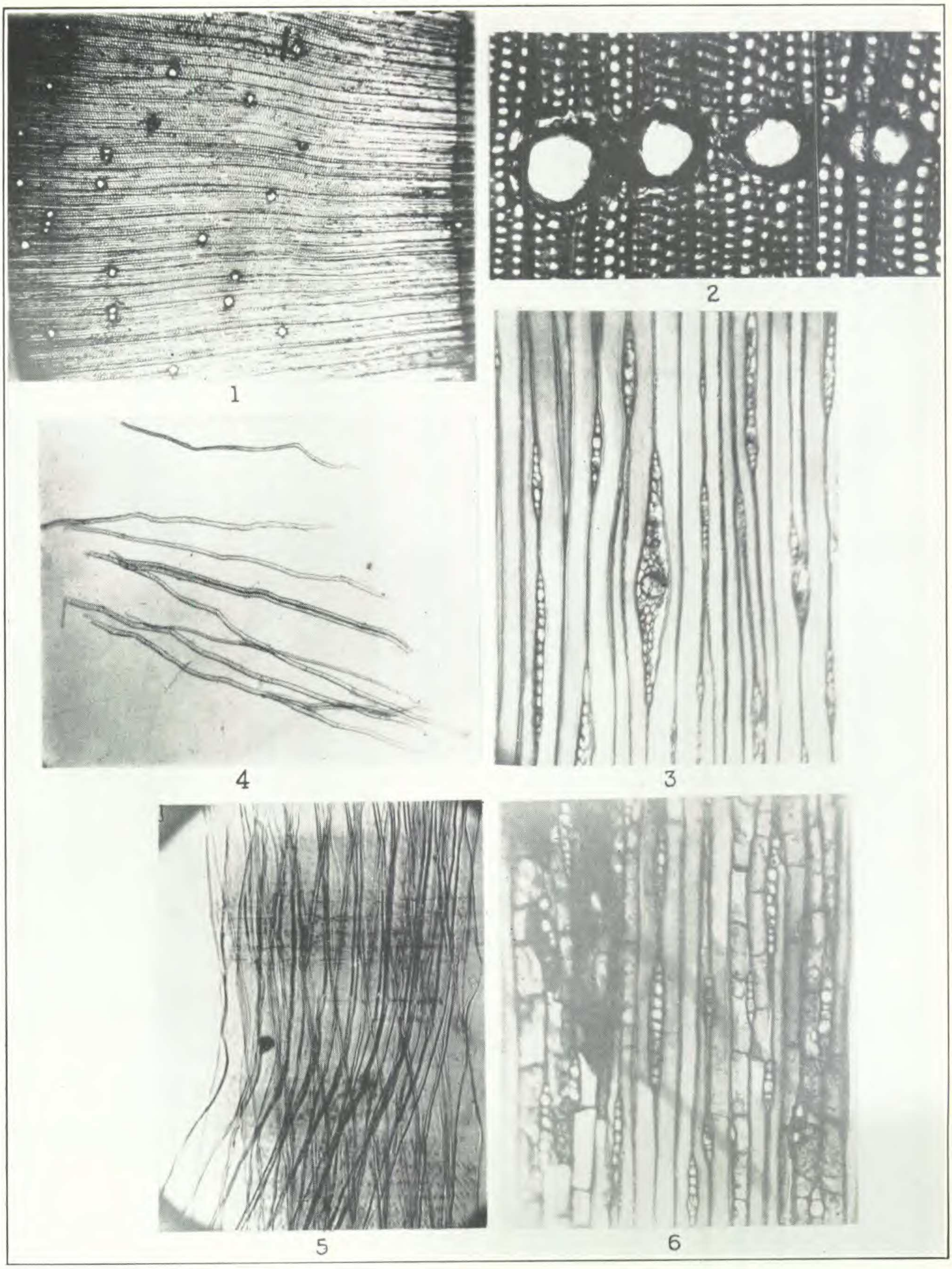
Fig. 2. A row of 4 resin ducts. Note the resin duct on the extreme right branching to form the fifth one. The cells between these resin ducts are all thin-walled parenchyma cells. × 100.

Fig. 3. Concentrimural tracheids showing the curvature and reduction in diameter where they pass the larger wood rays, particularly the fusiform ray. × 100.

Fig. 4. Crooked and deformed tracheids. × 13.

Fig. 5. The crossing of the alternate tiers of tracheids in crooked-fibered material. × 100.

Fig. 6. This figure gives some idea of the extent of the wood parenchyma and the septate tracheids in the region of a series of resin ducts as shown in fig. 2. × 100.



BERKLEY—SOUTHERN PINE

EXPLANATION OF PLATE

PLATE 11

Fig. 1. The diffraction patterns of the concentric laminae in the cell walls as revealed by the Spierer lens. These are typical concentrimural tracheids. × 900.

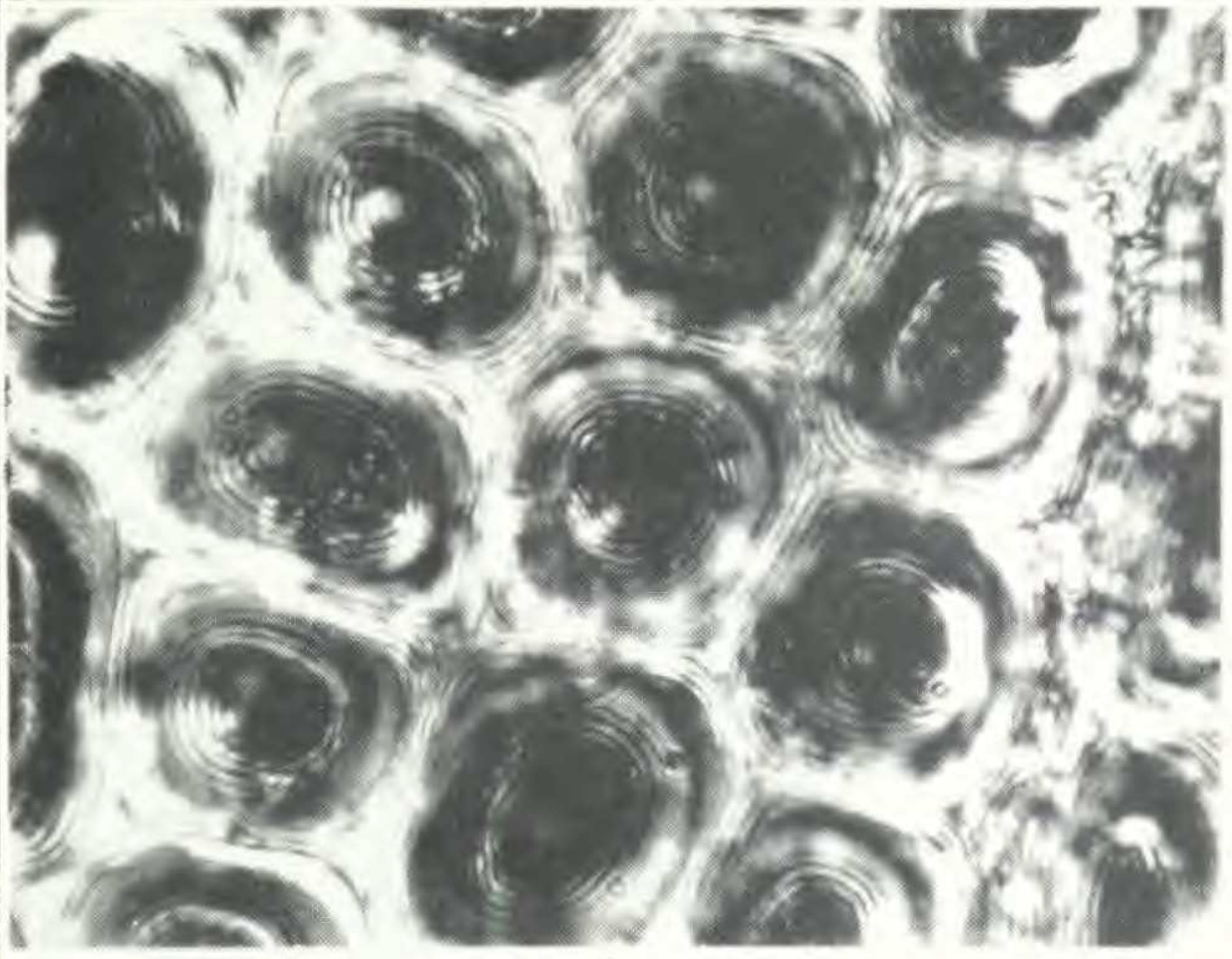
Fig. 2. The concentric laminae of the spring wood cells under direct illumination. This photograph was taken by the use of an ordinary oil-immersion lens. × 900.

Fig. 3. The diffraction patterns of the laminae as shown in the longitudinal section with the Spierer lens. The focus was adjusted on the cell walls and the lumen appears as a dark band between them. × 900.

Fig. 4. A layer of torquimural tracheids (the darkest area) within the summerwood portion of an annual ring. Note the sharp demarcation between the concentrimural cells and the torquimural cells at the inner edge of the latter (to the right) and the gradual disappearance of the torquimural cells on the outer side (to the left) where the two types of cells are intermixed. × 100.

Fig. 5. A longitudinal section of torquimural tracheids showing the spiral checks. Note the striations between the checks. × 450.

Fig. 6. A cross-section of torquimural tracheids showing the interstitial spaces, the sharp demarcation between the primary and secondary walls, and the numerous radial checks in the latter. × 900.



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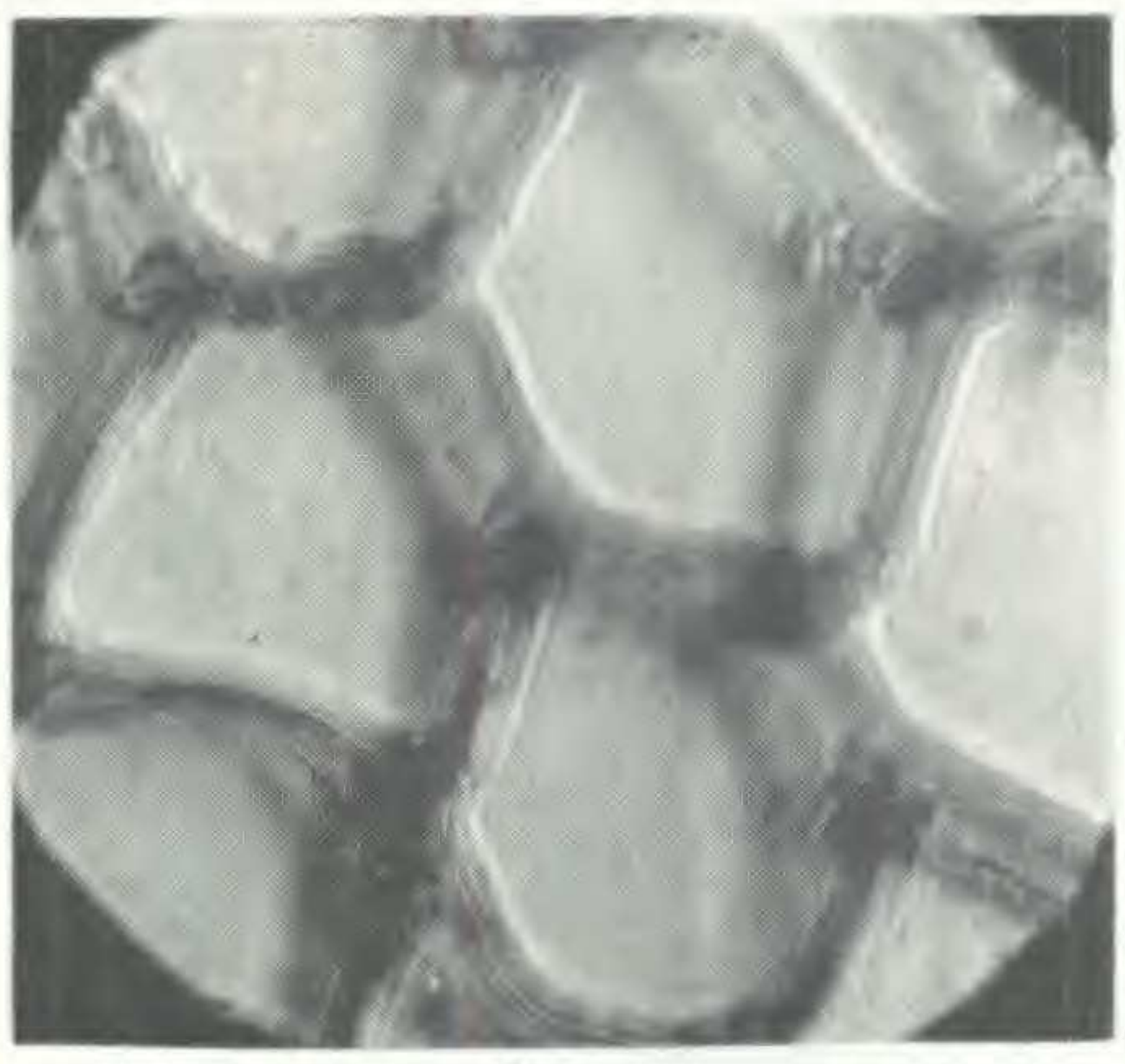

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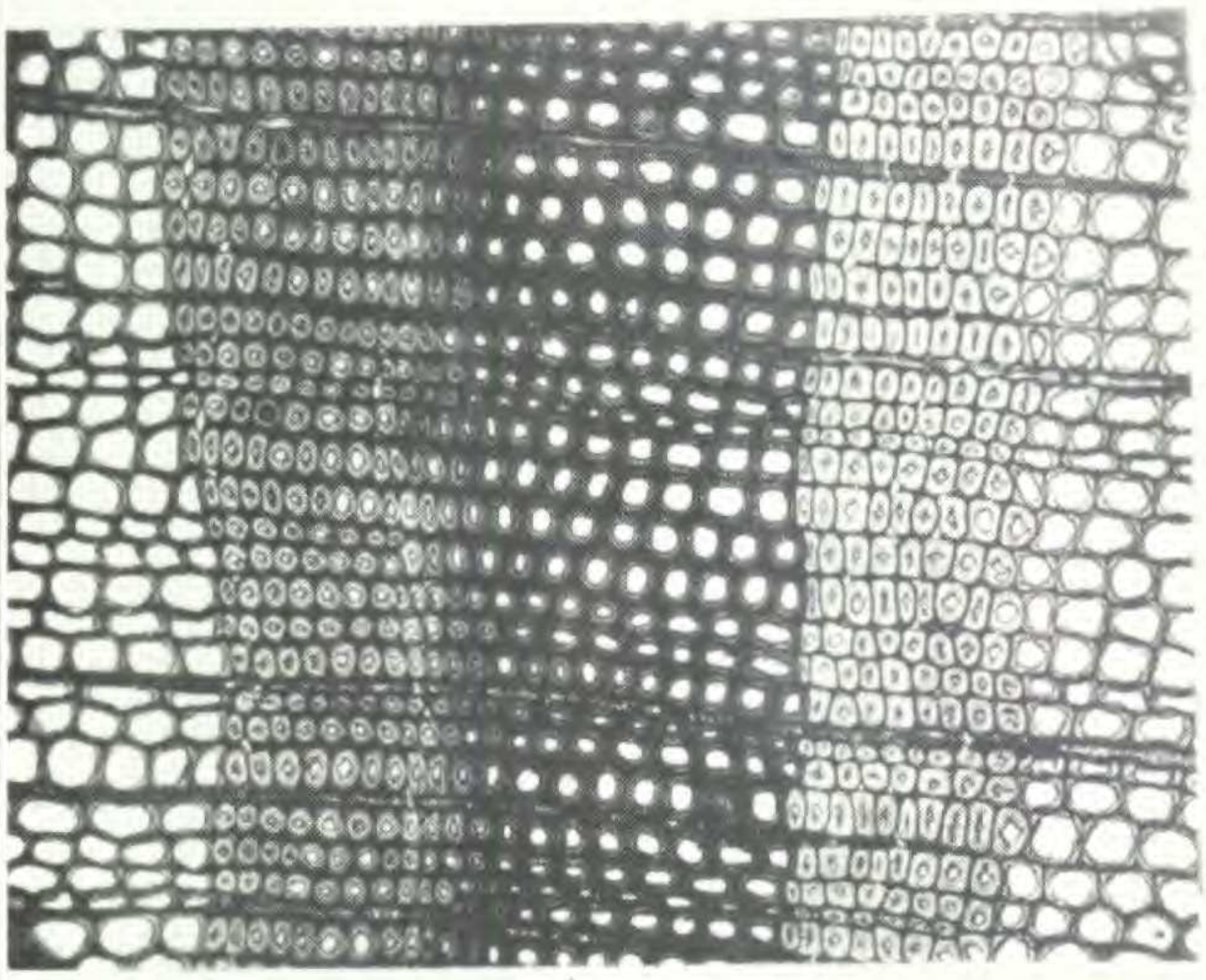

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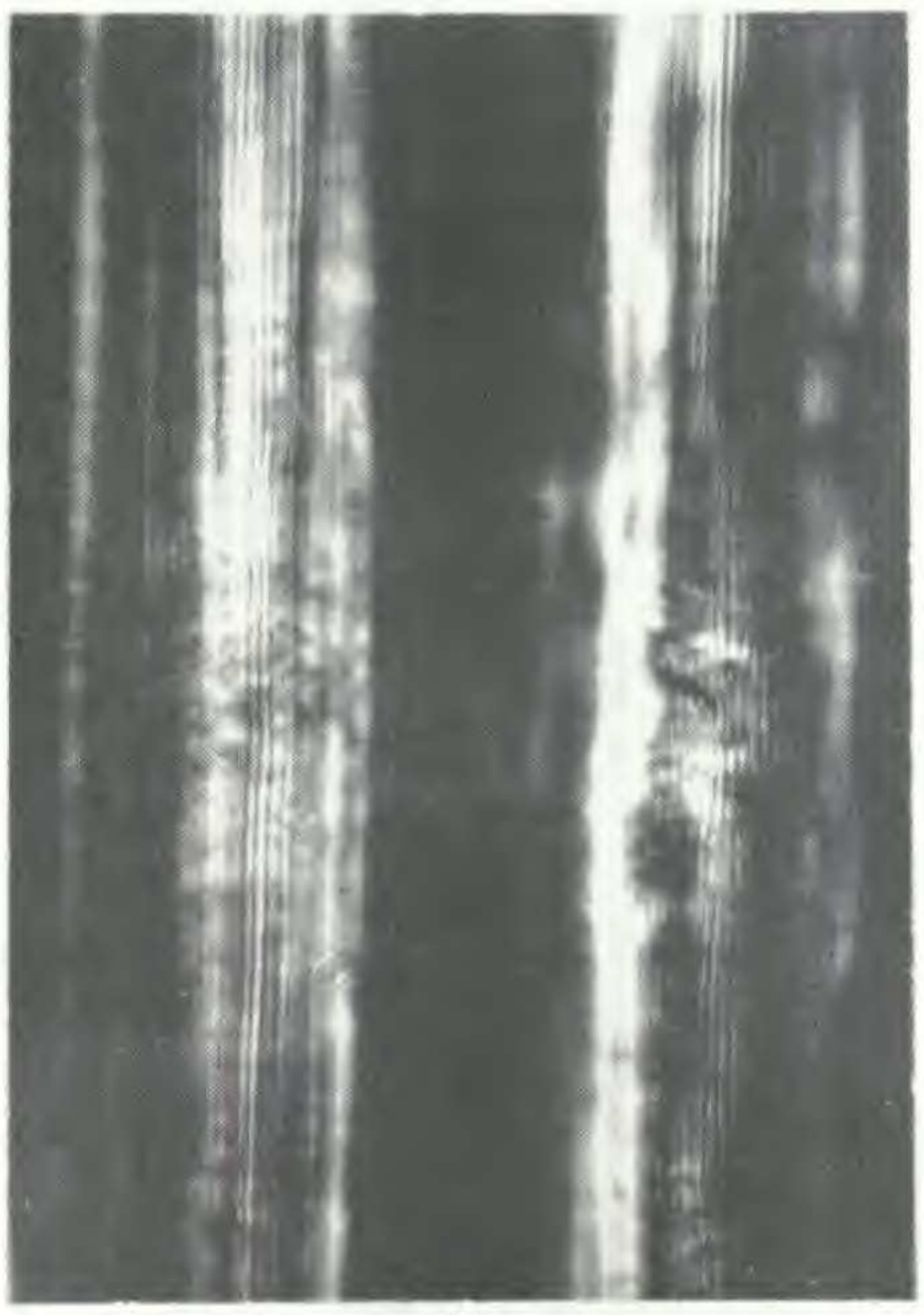

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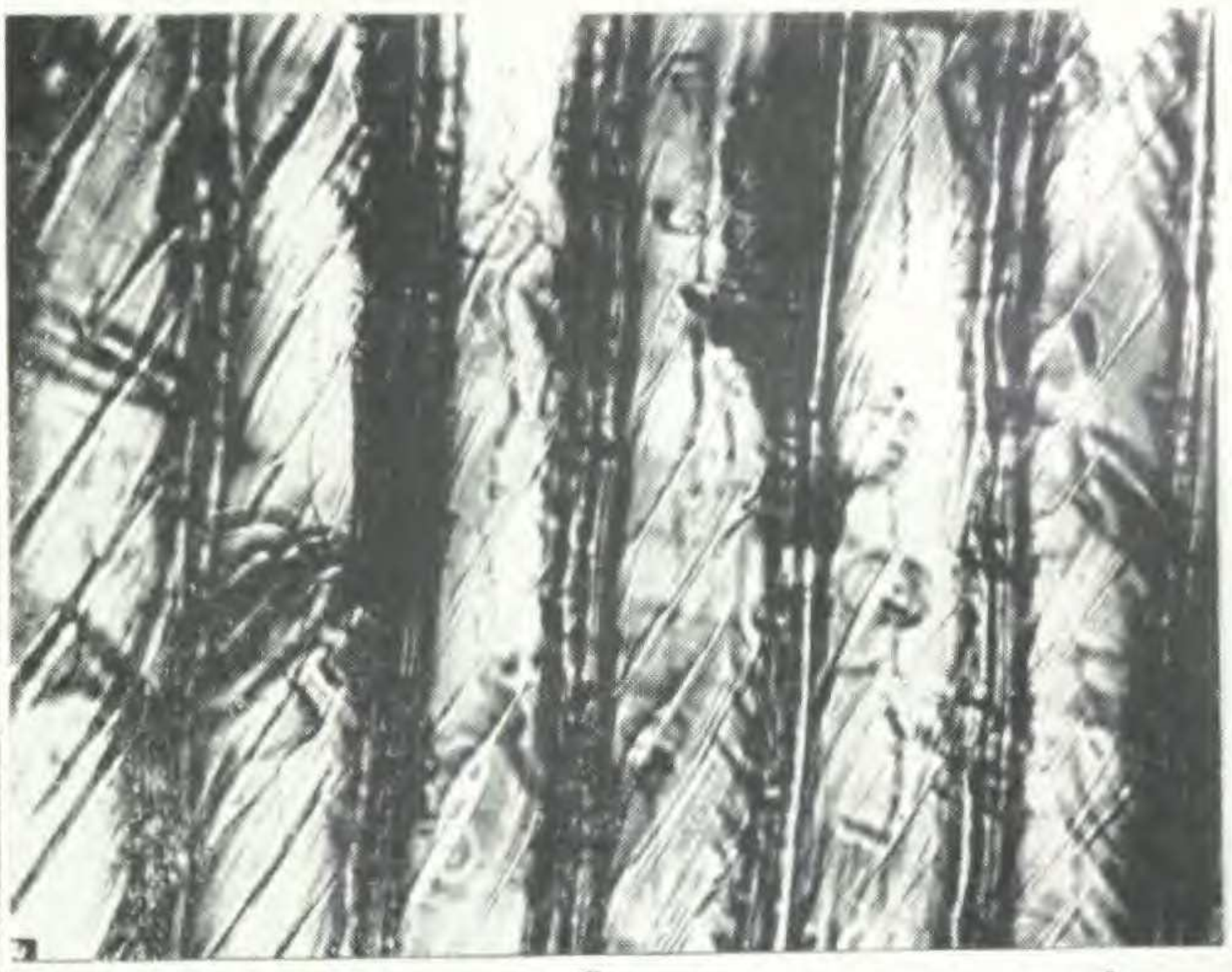

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BERKLEY—SOUTHERN PINE

Explanation of Plate

PLATE 12

Fig. 1. A cross-section of torquimural tracheids at the right and concentrimural tracheids at the extreme left. The radial striations in the secondary thickening are layers corresponding to the laminae of the concentrimural cells as illustrated in pl. 11, fig. 1. The cells to the extreme left do not have the radial laminae. Photograph taken by the aid of an ordinary oil-immersion lens. × 900.

Fig. 2. The torquimural cells as seen under the Spierer lens. Note the irregularity of the radial laminae. × 900.

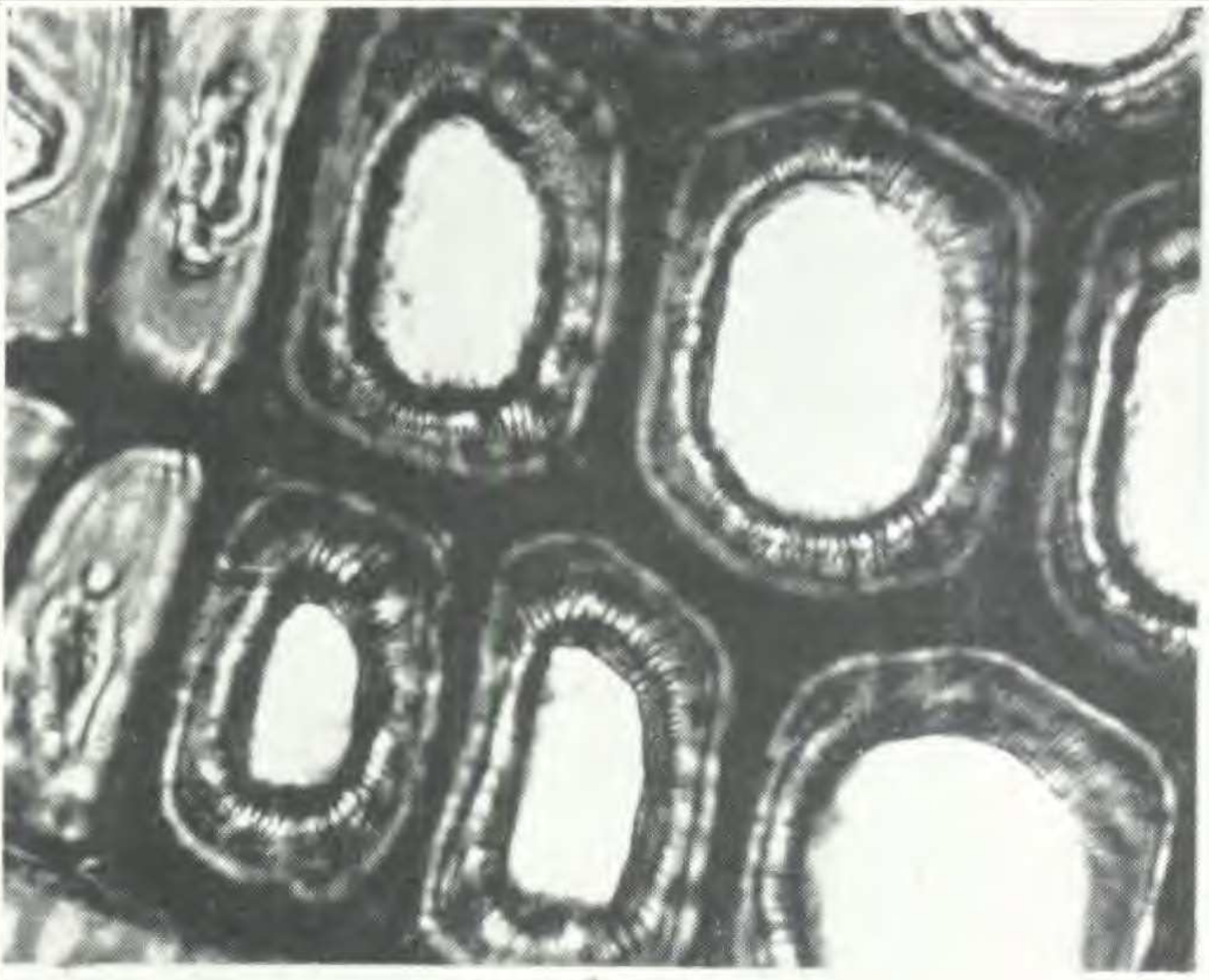
Fig. 3. Torquimural cells as in fig. 2 but showing in addition to the radial laminae of the secondary thickening the concentric laminae of the middle lamella. This area appears somewhat broader than it really is, due to the magnification of the diffraction patterns. × 900.

Fig. 4. The torquimural cells as seen by the use of the cardeoid dark-field condenser. Note the middle lamella which is distinct from the secondary walls which are checked in the radial direction. × 900.

Fig. 5. The same as fig. 4 but at lower magnification which shows more clearly the radial arrangement of the laminae in the secondary thickening. × 450.

Fig. 6. A longitudinal section of torquimural cells as seen under the Spierer lens. Note the spiral arrangement of the striations in the secondary thickening as contrasted with the parallel striations in the region of the middle lamella. This is a tangential section of the cell cutting through the radial laminae of the secondary thickening showing their edge view. Note the area between the middle lamella and the spiral laminae which shows no particular structure. This is due to the angle at which the laminae were cut, showing them on a side view as will be seen if this section is compared with a tangent to the cells shown in figs. 1–5. × 900.

Fig. 7. The spiral striations in the torquimural cells as shown under the dark field. × 900.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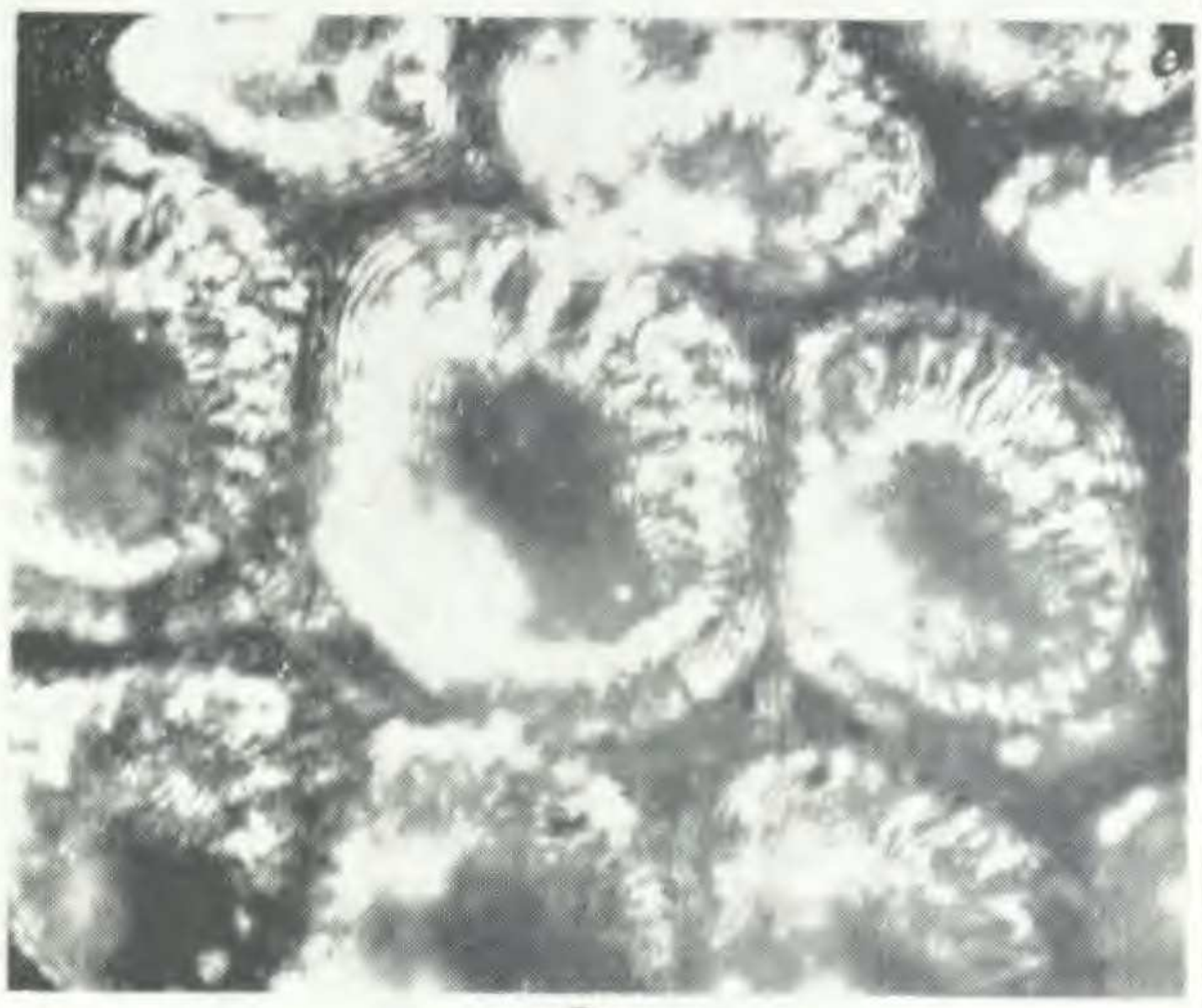
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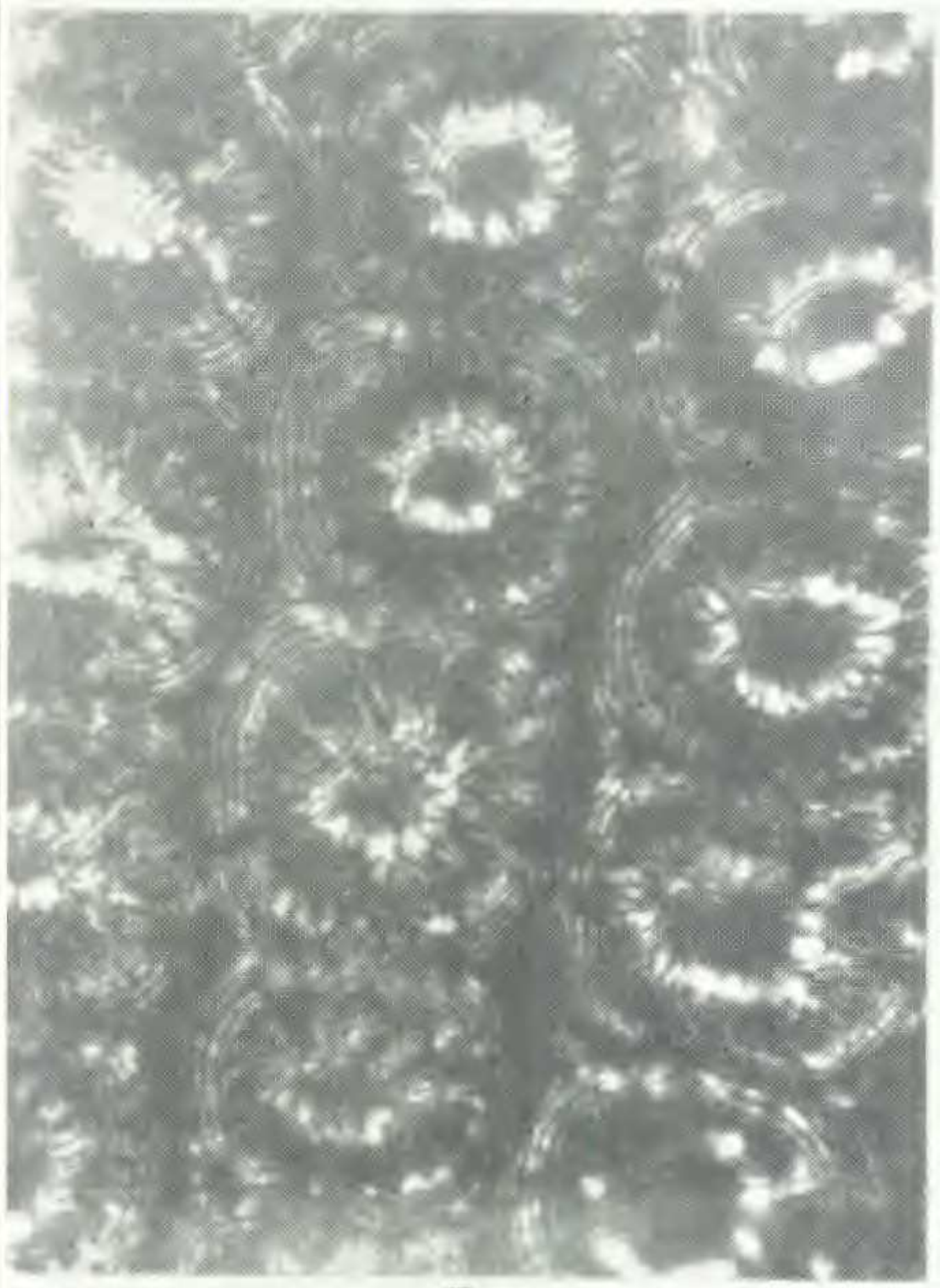
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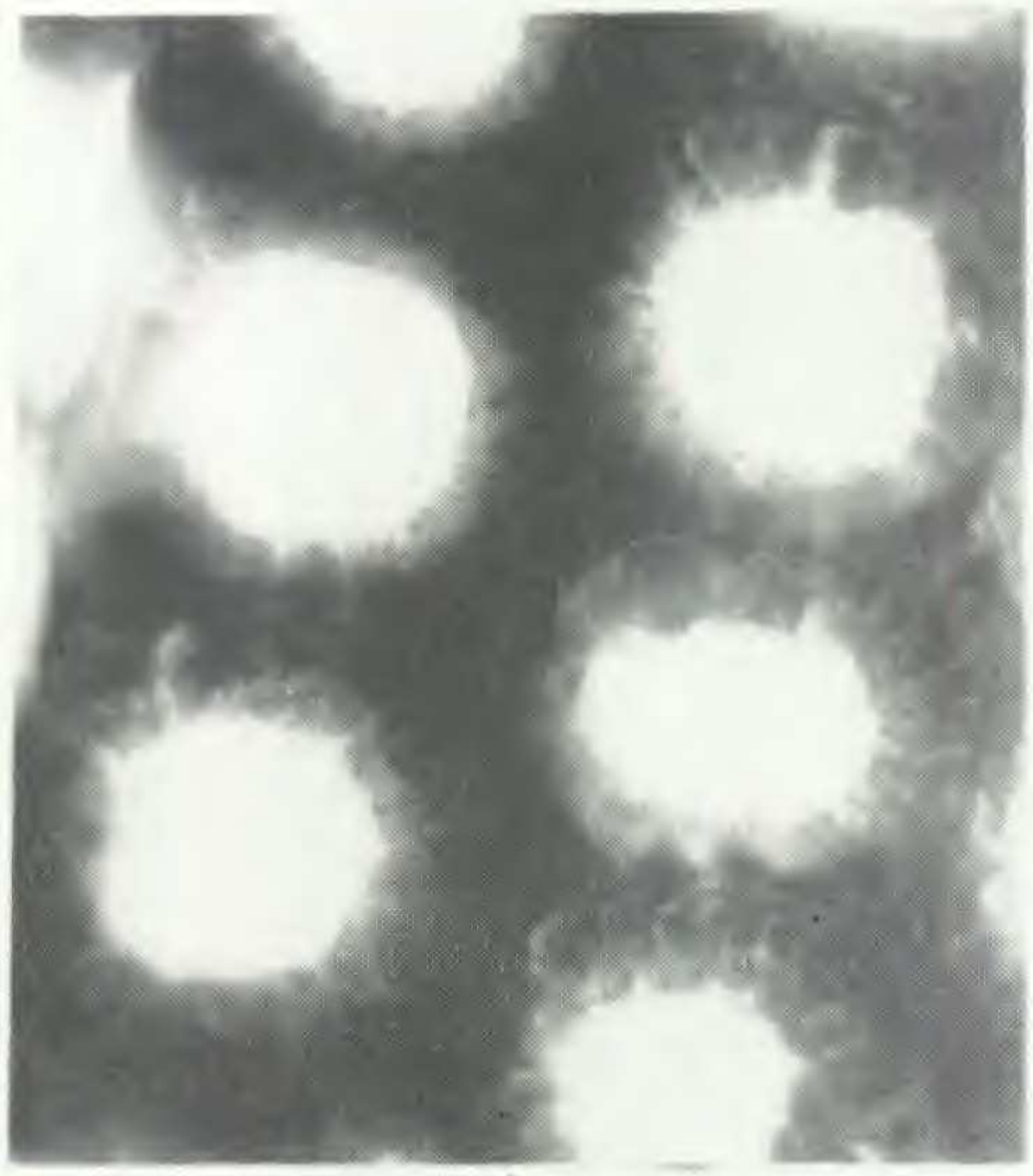
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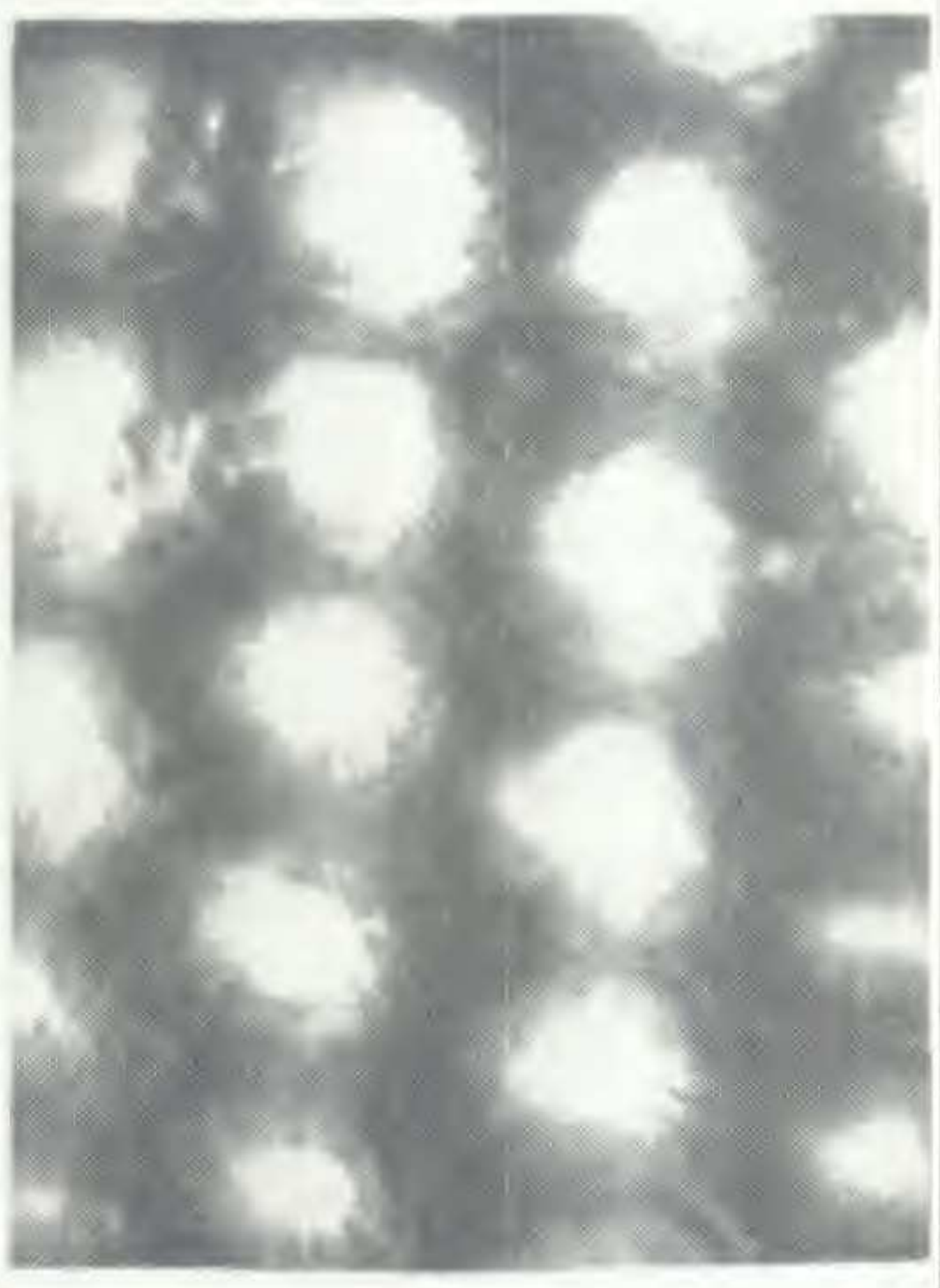
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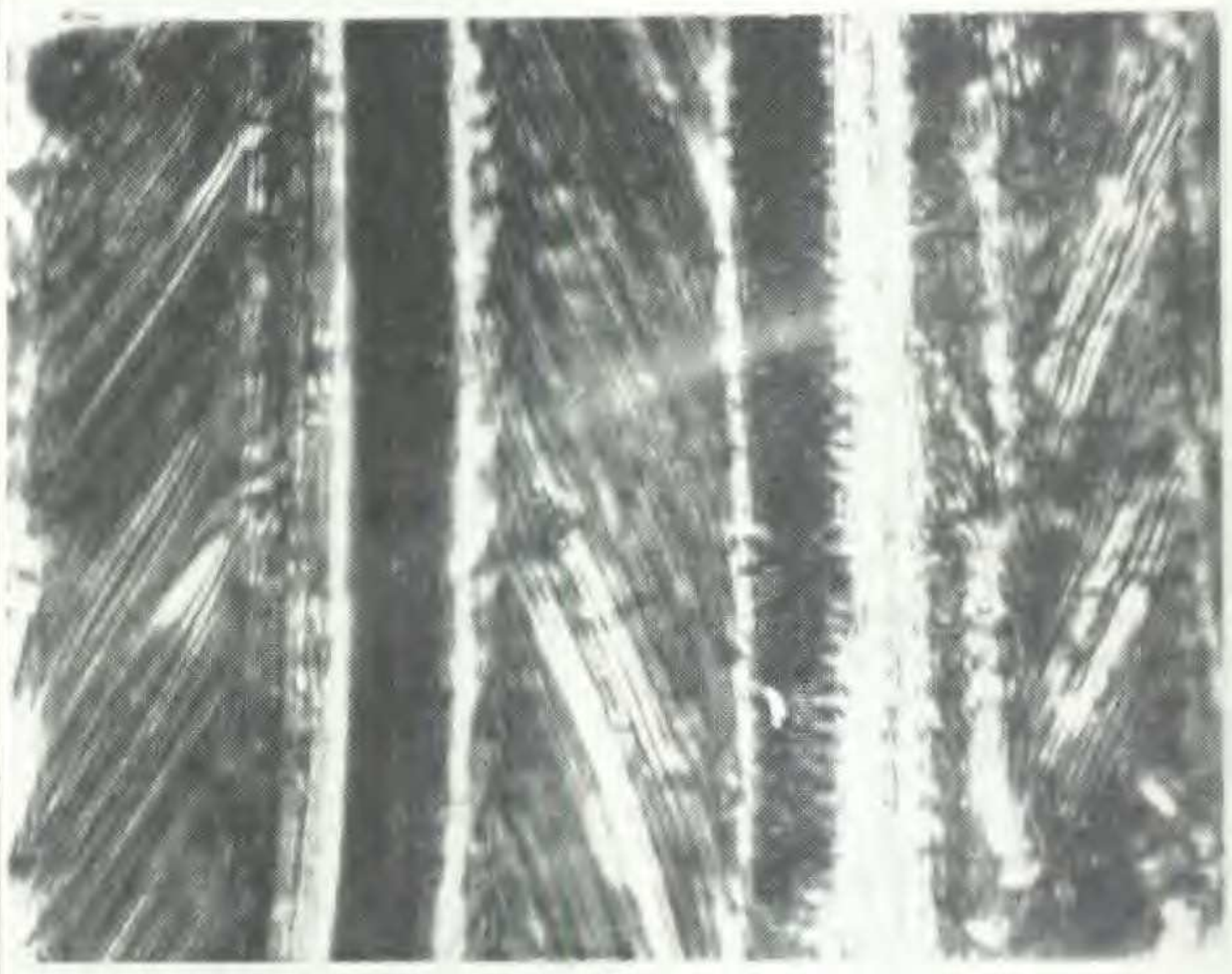
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BERKLEY—SOUTHERN PINE